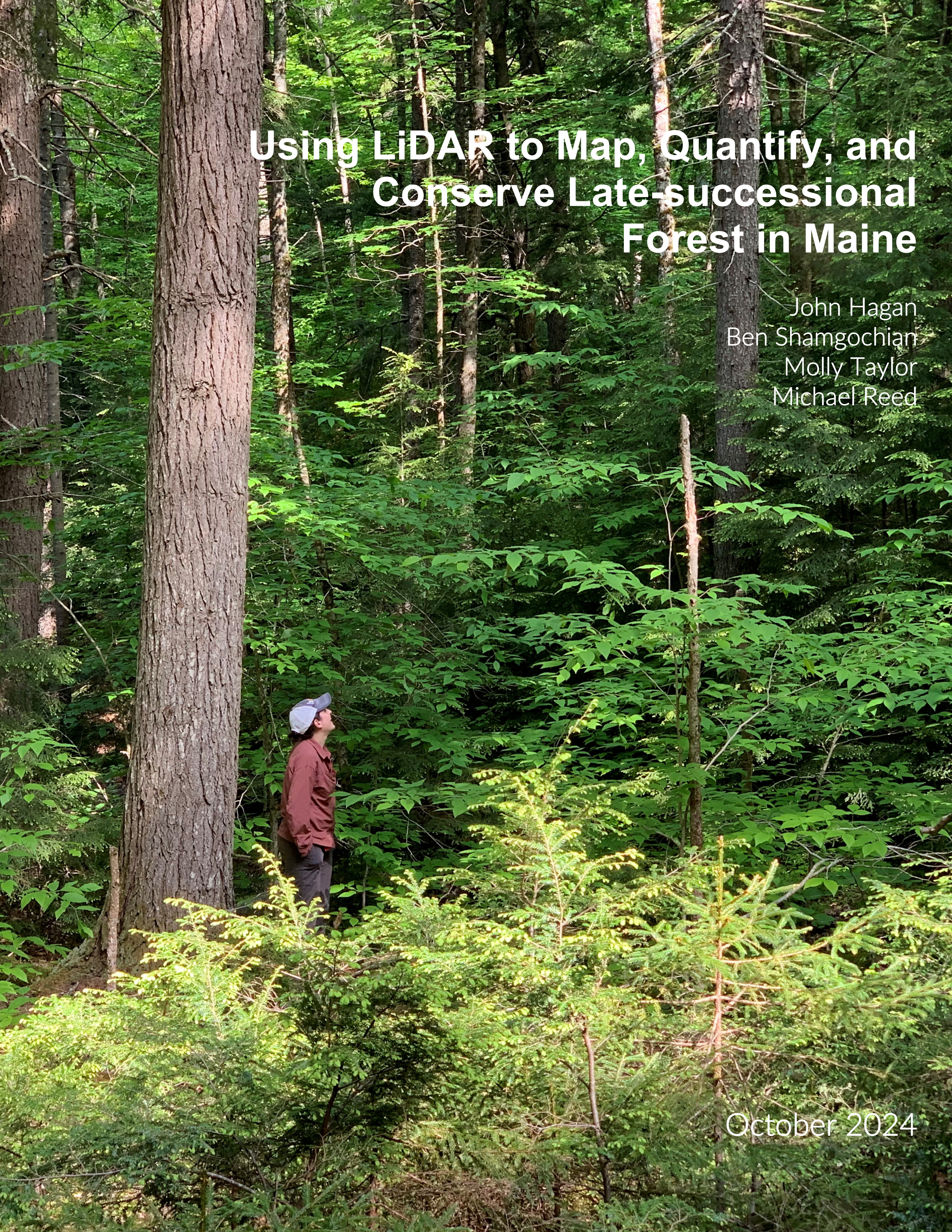

Using LiDAR to Map, Quantify, and Conserve Late-successional Forest in Maine

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Cover Photo

Molly Taylor in a late-successional stand near Greenville, Maine that we discovered using LiDAR (photo by J. Hagan)

OUR CLIMATE COMMON

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Ben Shamgochian with a 46-m tall (150') white pine (photo by J. Hagan)

Executive Summary

WHY THIS WORK MATTERS

Next to conversion of forest to other land uses, the loss of older forest age classes is a major threat to forest biodiversity worldwide. Late-successional and old-growth forests (LSOG) have a high density of large trees, large snags, and large downed logs, all of which are important to many species. The loss of these structural elements, as well as breaking the ecological continuity of LSOG stands over time, puts many forest species at risk. However, humans need wood for everything from paper and packaging to dimensional lumber for construction. Managing forests for such wood products results in a much younger forest across the landscape. Our challenge, then, is to manage for both wood production *and* LSOG forest. LSOG forest also has social value, irrespective of biodiversity benefits, and the Biden Administration made protection of mature and old-growth forest a national priority. To manage for LSOG forest, first we need a good sense of how much exists and where it exists. Then we can better manage the larger forest landscape for society's varied forest values. This study uses LiDAR (light detection and ranging) data to quantify and map LSOG forest in the 4.2-million hectares (10.3 million acres) of unorganized territory in Maine.

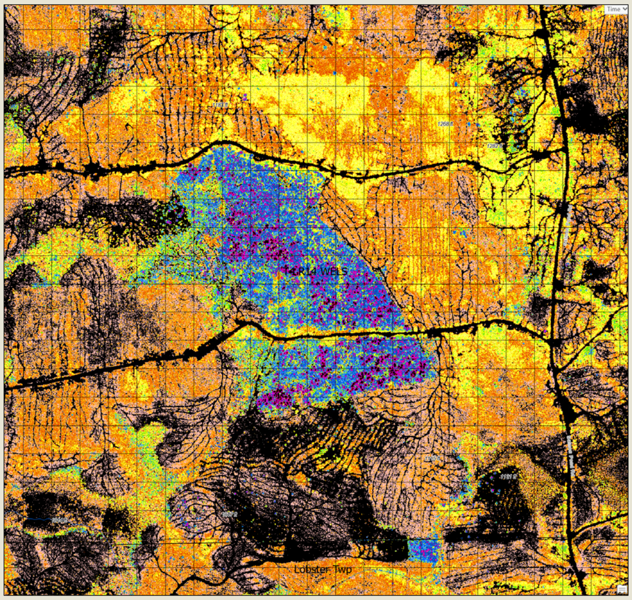

Figure A. The blue-magenta canopy height "signature" often indicates a late-successional stand in the unorganized townships of Maine. Grid=1 ha units.

METHODS

We used publicly available airborne LiDAR data, flown mostly between 2015 and 2018 in the unorganized townships of Maine ("study area"), to generate a canopy height model at $1m^2$ resolution for the entire area. In a commercial forest, LSOG stands "light up" because they are significantly taller than the surrounding managed forest (see Fig. A). Using sites of known forest successional stage, including true old-growth, we built a computer model based on eight canopy metrics that classified all 4.2-million hectares of the study area into one of four categories:

(1) Not LSOG (not late-successional or old-growth),
(2) Transitioning Late-Successional
(3) Late-successional, and
(4) "Old-growth-like" (Fig. B).

Although our classification was primarily structural (sizes of trees, amount of downed wood) and compositional (shade tolerant species), Transitioning LS forest typically had dominant trees 100-150 years old and LS forest had dominant trees 150-200 years old. Old-growth reference sites had overstory trees 200-400 years old. Note that our method was not designed to find stunted, high-elevation forest or old wetland forest. It was designed to find LSOG forest in the 85% of the landscape that would be accessible to logging, and where LSOG forest is most at risk in the near term. We plan to build a new model that maps just old wetland forest using LiDAR.

VALIDATION

We used two methods to validate the accuracy of the classification. First, the computer model (called *random forest*) does an "internal" validation using a subset of the reference-site data *not* used to build the model. This validation method indicated that the model correctly classified a hectare as Not LSOG or one of the three LSOG classes 94% of the time. The second validation method involved field verification—visiting novel hectares in the field to determine whether the computer model correctly classified the hectare. This more rigorous and expensive approach to validation showed virtually the same result—94% accuracy. We also challenged the model to distinguish more finely among the three LSOG classes. It performed well here too but struggled to distinguish between LS and true old-growth. Still, it correctly classified the older age classes most of the time, and thus provides an excellent map for directing landowners and conservationists to potentially exceptional LSOG stands. Ground verification is always essential.

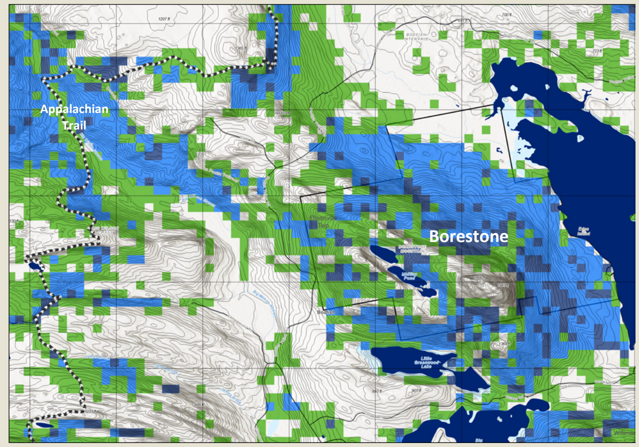

Figure B. An example of the computer model classification of each hectare in the landscape. Maine Audubon's Borestone Sanctuary southeast of Greenville is well-known to be late-successional forest. White=Not LSOG; Green=Transitioning LS; Blue=LS; Dark Blue="old-growth-like." Grid=1 km^2

HOW MUCH LSOG SUCCESSION FOREST REMAINS?

We estimate that about 16% of the unorganized territories of Maine was in Transitioning LS (green, Fig. B) and about 3% was in LS (blue, Fig. B). Only about 0.9% was classified as "old-growth-like." Fig. C summarizes percentages for different landscape units/ownerships. LSOG stands have a significantly higher density of late-successional forest characteristics than the average commercial forest stand. In our view, all LS stands should be conserved (or managed lightly) because of their increasing rarity. The model was not good at distinguishing between LS and true old-growth. We plan to build a more refined model to distinguish between just these two classes using a larger suite of canopy metrics.

HOW BIG (or SMALL) ARE LSOG STANDS?

Because the computer algorithm classified each hectare independently, we were able to examine the size class distribution of the three LSOG classes. For example, in the 4.2M hectare study area, there were 21,783 distinct parcels of LSOG forest in the 1-5 hectare area class, totaling some 58,621 hectares. At the other end of the area distribution, there were 386 stands ≥ 250 ha, totaling 432,000 hectares. While it is tempting to focus only on the larger stands for conservation prioritization, that would be a mistake. Some of the most vulnerable species to forest age (many mosses and lichens) can persist in small patches of forest for decades. If retained, these many small patches could function as source populations for the surrounding forest as it regrows. At the same time, larger stands allow for species and functions that require larger areas. The important point is that both large stands and the thousands of widely distributed small patches contribute to ensuring healthy populations of LSOG-related species in Maine's unorganized townships.

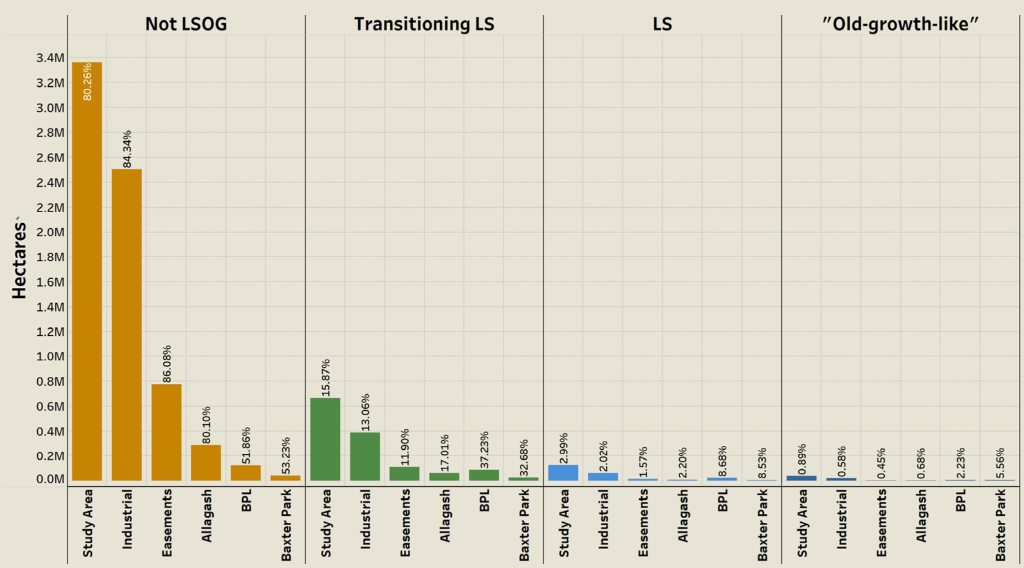

Figure C. Based on our computer classification model, the amounts (hectares) of Not LSOG, Transitioning LS, LS, and "old-growth-like" forest in different geographic units. The numbers above the bars indicate the percentage of the land unit in the indicated forest class. E.g. 8.68% of BPL ownership is in the LS class.

WHERE IS LATE-SUCCESSIONAL FOREST?

Maine Bureau of Parks and Lands (BPL) had the highest percentage of LS forest (8.7% of ownership), reflecting an ecological emphasis on publicly held forest. By contrast, only 2% of commercial timberland was classified as LS forest. Despite this small percentage, private commercial timberlands still contained most of the remaining LS forest (60,148 hectares) because private commercial timberlands made up 85% of the study area. Therefore, private commercial forest is an important place to focus LSOG conservation efforts. Baxter Park, BPL's Ecological Reserves, and some private conservation lands are the only places that are likely growing new LS forest.

HOW FAST ARE WE LOSING LSOG FOREST?

Because the LiDAR we used was flown 6-8 years ago, we were able to calculate rate of loss of LSOG forest using Global Forest Watch forest change data, updated through 2023 (Table A). We estimated that the LS forest class is being lost at a rate of 1.4%/year for the entire study area. Within the study area, BPL was losing LS forest at a relatively slow rate of 0.6%/year, but private commercial landowners were losing LS forest at 2.2%/year, or nearly 4 times as fast as public land. Expressed in terms of half-life, half of the remaining LS forest on private commercial forestland would be gone in 21 years, again arguing for a focus on private commercial timberlands for LSOG conservation.

Table A. Estimates of the rate of loss of LS stands from selected ownership types.

	LS Initial Hectares [1]	LS 2023 hectares	LS Annual Rate of Harvest	Half-life (years)[3]
Study Area	135,672	125,581	-1.40%	35.0
Maine BPL (Bureau of Parks and Lands)	21,135	20,523	-0.60%	96.1
Maine BPL (without Ecological Reserves)	17,381	16,388	-0.97%	48.2
Baxter State Park [2]	6,496	6,471	-0.02%	787.0
Large "industrial" forest owners	68,723	60,603	-2.16%	20.8

CONSERVATION STRATEGIES

In this report we outline six strategies for LSOG conservation. We can anticipate the need to pay commercial landowners for LSOG forest because it can be a financial cost to maintain stands in these older age classes. Some strategies include: using our new LSOG maps to target areas for public acquisition; the purchase of precision LSOG easements, paying landowners to forgo the timber revenue from LSOG stands; and engaging the forest carbon offset market to conserve LSOG stands because they have high volumes of carbon relative to younger forest. As the price of carbon goes up to $15-$25/tonne for CO_2 in the voluntary carbon market, LS stands are close to being worth more for their carbon than for their wood value. Fiduciary responsibility of commercial forest owners would argue for paying attention to this rapidly emerging opportunity. Simultaneously, some landowners are willing to manage LS stands in a lighter fashion. Forest certification systems (SFI and FSC) do not prevent LS stands from being harvested.

CONSERVATION IMPLICATIONS

In other parts of the world, we have seen the biodiversity implications of a long history of forest management. For example, Sweden, which has forest types similar to Maine's, has a long list of "red-listed species" (equivalent to our threatened and endangered species), most as a result of the loss of older forest age classes. Species conservation becomes expensive when species become endangered; it is more cost effective to conserve them before they become endangered. We need a social conversation about how much LSOG forest we want and how we want it distributed. Then we can take action to get there. We need commercial landowners and conservationists to bring their respective skills together to change the trajectory of LSOG loss. We believe this can be done, while maintaining or even growing a healthy forest products economy, if we all work together.

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INTRODUCTION

Next to conversion of forest to other land uses, the loss of older forest age classes is the biggest threat to forest biodiversity worldwide.[1,2,3,4] This is not a surprise. Humans need a lot of wood to survive and thrive, from dimensional lumber for our homes to cardboard boxes for shipping. As a result of these needs, we affect the age-class distribution of forests worldwide. To produce the volume of wood we need, the age of the forest becomes much younger than the natural lifespan of most tree species.[5,6,7] As a result, managed forests worldwide do not get as old as they would in the absence of human needs. Late-successional and old-growth forest has become greatly diminished as a result (Fig. 1).[8,9,10]

Also not surprisingly, much of forest biodiversity evolved in landscapes where trees *did* reach their natural lifespan. When nature takes its course, trees might live two or three hundred years in a typical spruce/hardwood forest of northern New England. Trees grow old and die from natural causes. Living trees often become snags (standing dead trees), or they may blow down and become large logs on the forest floor.[11,12] Many plant and animal species evolved to take advantage of big and old trees (and logs).[13,14,15] For example, large old trees are often pocked with the nesting or feeding cavities of many bird species. Large old trees often have cracks, broken branches, and large crowns that serve as habitat for many different species.[16,17] Many epiphytes (mosses and lichens) prefer large old trees, and they can become rare or endangered in places where there are few old trees for substrate.[18,19] Large old trees often have root cavities at the base, which can serve as den sites for different mammals, depending on the size of the tree and the cavity.[20,21] In short, many species—birds, mammals, lichens, insects, mosses, and fungi, need some old trees (and logs) in the greater landscape to persist.[22,23,24,25] The biodiversity conservation challenge is how to maintain the functions of large old trees, and stands of large old trees, in forest landscapes managed to meet our need for wood.

It has been difficult to map and accurately quantify older forest in large forested landscapes like Maine. If we do not know how much we have and where it is, it is difficult to develop conservation plans to keep it, either across the larger forest landscape or at the scale of a sustainably certified timberland owner. This report is about how we tested a relatively new remote sensing technology, LiDAR (light

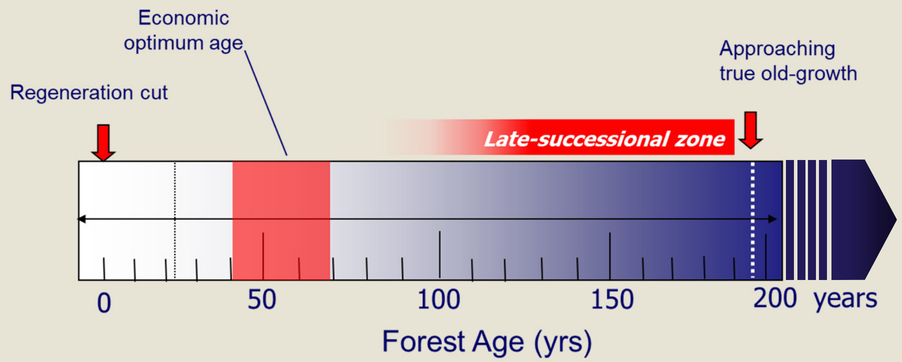


Figure 1 – The financial optimum age for most forest managed for forest products in northern New England is 40-60 years old, or 60-100 for some hardwood sawlog products. However, important ecological characteristics develop when trees are 100 to 200 years old. The challenge is how to maintain these older forest functions, and associated species, in a managed forest landscape, which makes up 87% of the unorganized territories of Maine.

detection and ranging), for mapping late-successional and old-growth (LSOG) forest in the vast unorganized townships of Maine. Ground surveys of the entire 4.2-million-hectare (10.3-million-acre) study area would be prohibitively expensive. However, if LiDAR can do the job remotely, we will have a new tool for mapping and quantifying how much LSOG forest remains, and where it is. To date, we have had to rely on expensive ground surveys that could not possibly screen the entire area of interest.

In this study our goal was to locate, quantify, and map LSOG forest in the unorganized townships of Maine using publicly available LiDAR. LSOG stands generally have a high density of late-successional forest features, such as large trees, snags, and downed logs. Just as old-growth was lost with European settlement of Maine in the 1700s and 1800s, much late-successional forest has also now been lost in the late 1900s and early 2000s. As you will see in this report, we estimate that about 3% of Maine's unorganized territories is in the more highly developed, ecologically rich late-successional stage today, and declining. If LiDAR works as a tool to locate remaining late-successional stands, we can then understand who owns it, how much there is, and where it is, across a 4.2-million-hectare area. If LiDAR works, we will have a new tool we can use to conserve this ecologically significant and increasingly rare forest.

We first need to know how much LSOG forest we have and how it is distributed across the larger forest landscape. Then, we can make informed decisions about how much we want, and how we want it distributed.

This report comes on the heels of renewed national interest in conserving "mature and old-growth" forest. In April 2022, President Biden issued Executive Order 14072, also known as "Strengthening the Nation's Forests, Communities, and Local Economies."[26] The Executive Order called particular attention to the importance of mature and old-growth forests, and instructed the U.S. Forest Service to conduct a nationwide inventory of federal lands.[27] The Executive Order pointed out the role of mature and old-growth forests for their large stores of carbon in relation to climate mitigation, and for their importance to the nation's biodiversity. There has also been renewed focus on old-growth forest in the eastern U.S.[28]

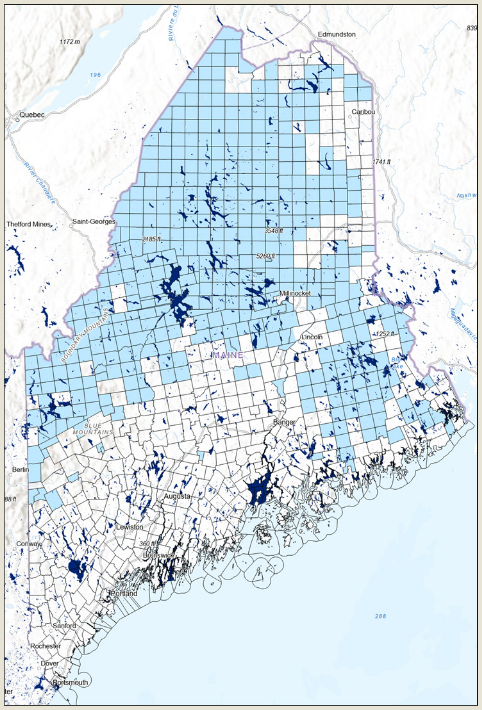


Figure 2 – The unorganized townships of Maine (blue), comprising 4.2M hectares (10.3-million acres), or nearly half the state. These townships are "unorganized" because there are not enough people living there to form a local government. About 90% of the unorganized townships are managed for timber and forest products.

Even if LiDAR works for the purpose of quantifying older forest age classes in Maine, we will still face the question of how we (as a society) balance the forest age-class distribution in the unorganized townships of Maine (Fig. 2). Do we rely only on public lands, which is only about 7% of the area, to provide our LSOG forest values? Or, do we also look to private timberland owners, who own 85% of the area, to help conserve old forest? This is more of a social than scientific question. To have the social conversation, however, we first need to know how much LSOG forest we have and how it is distributed across the larger forest landscape. Only then can we make informed decisions about how much we want, and how we want it distributed, and most importantly, just *how* we might achieve that societal goal while preserving rural, vibrant, forest-based communities. If we want it all, we're going to have to do some hard work, and we're going to have to do that work *together*.

Maine's Unorganized Territories

Maine is an unusual place in the eastern U.S. Nearly one-half of the state is classified as "unorganized," meaning not enough people live in this area to form a local government (Fig. 2). This area was divided up into "townships" in the mid-1800s—a misnomer since there are no "towns" in these townships. Despite great effort in the 19th century, the state of Maine could not convince people to settle here—too many trees to clear and rocks to grub out of the soil for agriculture.[29] To this day, most townships have no permanent human habitation. Many don't even have seasonal human habitation.

But these townships are not devoid of human impact. Most of the unorganized territories of Maine are owned by large corporate landowners who purchased the land primarily to make money from the timber. Thus, most of the forest is much younger than it would be otherwise. Sometimes natural events, like outbreaks of the native spruce budworm or ice storms, can alter the age-class of the forest for decades.[30,31] But today, the younger condition of most of the forest is a result of management for forest products—pulp for paper-making, lumber for construction, and many other products, from wood fiber insulation to golf tees.

LiDAR

LiDAR is an "active" remote sensing technique that fires thousands of laser pulses at the ground every second, usually from a plane (i.e., *airborne* LiDAR). The energy is generated by the laser; that's what makes it "active." By contrast, traditional aerial photography senses sunlight reflected off the forest (hence "passive"). Each LiDAR laser pulse bounces off the ground (or a treetop) and returns to the plane overhead (Fig. 3). The difference in return time (microseconds—or millionths of seconds) between the ground reflections (last return) and the treetop reflections (first return) provides a very accurate estimate of tree height (within about 10 cm, or 4 inches). Each pulse of LiDAR might reflect off 2 or 3 surfaces before it finally hits the ground. As a result, LiDAR generates a cloud of points, where every point has a very accurate and precise x (latitude), y (longitude), and z (canopy height) coordinate. A highly precise and accurate "picture" of the forest emerges in the form of a point cloud.

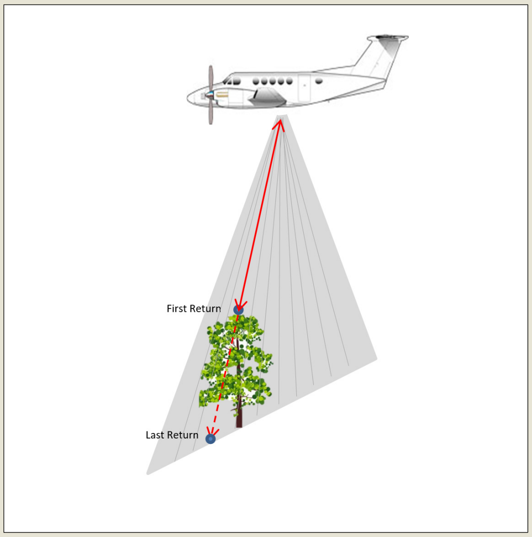


Figure 3 – LiDAR is an active remote sensing method that fires thousands of laser pulses at the ground per second. The laser signal bounces off trees and ultimately the ground. The difference in time it takes the laser reflection to return to the sensor on the plane indicates the height of the tree with about 10 cm (4") accuracy.

While replicating a study of birds and forestry in the early 2020s, originally conducted in the early 1990s,[25,32,33] we discovered that LiDAR could show us precisely where remaining LSOG forest was in our 240,000-hectare (600,000-acre) study area in the Moosehead Lake region of Maine.

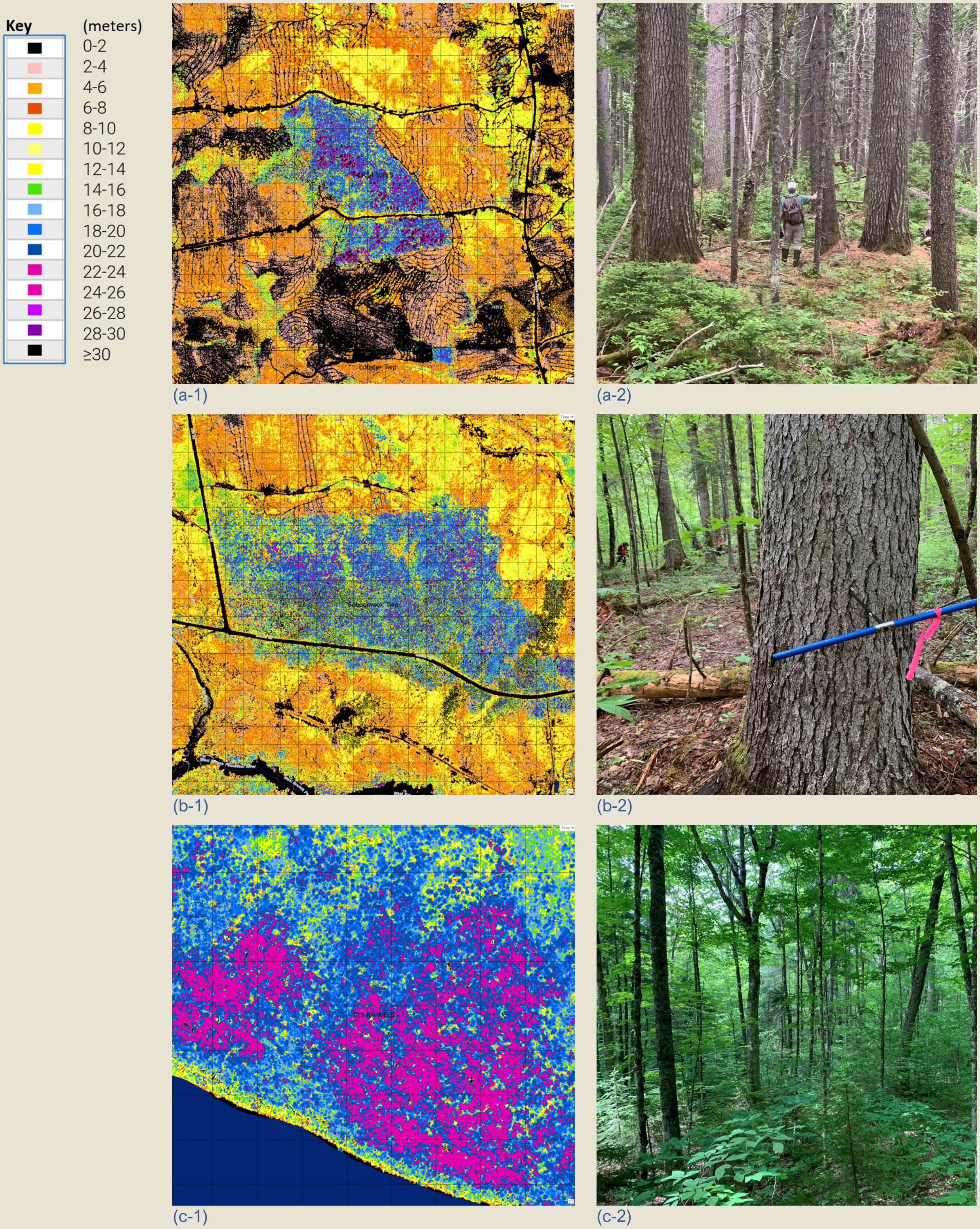


Figure 4 – Three examples of LiDAR-derived canopy height models of LSOG stands (left panels). We discovered during the "30-Year Bird Study" in 2021 and 2022 that the "blue-magenta" height signature almost always indicated an LSOG stand. Pictures to the right show what the blue-magenta area in the left panel looked like on the ground. The red spruce in Fig. 4b-2 was 253 years old, based on the increment core. This stand is slated for harvest in 2024. Left panel grids=1 ha units.

This was especially helpful because LSOG forest had become uncommon and difficult to find in the study area, yet we needed this forest age class in our sampling design to properly replicate the 1990s study.

Fig. 4 shows three examples of LSOG forest using a canopy height model derived from LiDAR data. During the bird study, we discovered that the "blue-magenta" signature almost always indicated a forest stand with a dominant canopy older than 100 years, and often 150-250 years old. We speculated that we might be able to use the LiDAR-derived canopy height model to map and quantify LSOG forest for the entire unorganized township area of Maine (see Fig. 2).

Using LiDAR to find LSOG forest

Other researchers have used LiDAR to find and quantify LSOG forest.[34,35,36,37,38,39] Recently, a study in boreal Canada showed that LiDAR could even distinguish between different ages of LSOG forest.[40] Because of the large area covered by LiDAR flights, and its high resolution, some researchers were able to locate old-growth forest that was not previously known. We have been able to do the same in this study.

LiDAR has been used to locate old forest in the tropics,[38,41,42,43,44] the subtropics,[39,45] the temperate zone,[46,47,48] and boreal forests.[39,49] Most of this research has been done in the last five years. Clearly, LiDAR is a new tool that has broad-scale (global) applicability for identifying LSOG forest. LiDAR has also been used to link old forest to forest biodiversity.[50]

Although this study's primary focus is on the identification and location of LSOG forest for biodiversity conservation, it is well-known that old forest also can contain large stores of carbon because of the large size of trees.[51,52,53] There is much interest in retaining old forest as reservoirs of carbon because of climate change.[54] We explore an array of LSOG conservation approaches in the Discussion section, including carbon offsets through LSOG conservation.

What this work is NOT designed to do

Although we tried to distinguish true old-growth (OG) from late-successional (LS) forest in this study, our primary goal was to find LSOG forest in the "operational zone" of the larger forest landscape. The operational zone is mostly the areas where logging is feasible, which is the vast majority of the study area, and where LSOG forest is most at risk. This study did not set out to find stunted old wetland forest or stunted high-elevation forest. It is hard for us to know how much of Maine's wetland forest and high-elevation forest might be in an LSOG condition. Using different training data, we plan to explore these types of forest in future work.

Ben Shamgochian in an LS class softwood (pine/spruce) stand (photo by J. Hagan)

Methods

Our focus study area was the unorganized townships of Maine (see Fig. 2), plus a few organized townships on the periphery to fill in gaps, totaling about 4.2 million hectares, or about 50% of the land area of Maine.

Generating a canopy height model

We used publicly available LiDAR data flown from 2015 to 2018 to generate a canopy height model for the study area. We downloaded LiDAR data "tiles" (about 1 sq km each) using the USGS National Map Download Application (v2.0).[55] LiDAR data files are quite large. The entire study area was about 4 terabytes of compressed LiDAR data (LAZ files); processing the uncompressed data required about 5x more disk storage space.

We used ARCGIS Pro software[56] to generate a canopy height model of the study area from the raw LiDAR data. The LiDAR pulse rate of this publicly available LiDAR data (3-6 laser pulses per square meter) was sufficient to allow us to generate a canopy height model with 1 meter horizontal resolution and about 10-centimeter vertical (height) accuracy. Although the LiDAR data were 6-8 years old at the time of this report, the height of LSOG forest had likely changed little between data collection and the time we processed the data (2023), except where LSOG stands were harvested *after* the LiDAR was flown.

The canopy height model generated a very accurate and fine-grained "picture" of the forest canopy height (Fig. 4 a,b,c). Using our color symbology for 2 meter height classes (Fig. 4), areas with a cluster of blue-magenta pixels (indicating forest 22 meters and taller) were almost always LSOG stands when we subsequently ground-truthed them on the bird study.

Modeling LSOG forest

We were primarily interested in quantifying and mapping LSOG forest that had a high density of late-successional structure with no recent (~50 years) evidence of harvesting because it is uncommon to rare in the unorganized townships and, in our view, should be a priority for conservation. However, because we could distinguish among younger late-successional forest, older late-successional forest, and true old-growth in the field, we attempted to build a computer algorithm that could also distinguish among these three LSOG classes using LiDAR canopy metrics. See Table 1 for our classification system and definitions.

When in the field, we classified stands into one of these classes (including "Not LSOG") based on an array of stand structural characteristics, including sizes of trees, presence/absence of recent logging activity (skid trails and sawn stumps), presence of long-ago logging activity (e.g., one or a few sawn stumps >50 years since harvest), presence/absence of shade-intolerant tree species, and abundance of large snags and downed wood. Especially for the LS and Old-growth (OG) classes, we viewed historical aerial photos, mostly from the late 1960s, for any signs of skid trails at that time. We also cored one representative tree in many LSOG stands to get a sense of dominant overstory age, following the Maine Natural Areas

Program ecological reserve sampling design. Our field designations to class were statistically upheld by analyses of our plot vegetation data (see Fig. 9 later in report).

The definitions of 'old-growth,' 'primeval,' 'ancient,' 'late-successional,' and 'mature' forest can vary greatly even among forest ecologists.[57,58] Some argue that age should be the main driver of the definitions and others argue it should be structure.[59,60] In our view, it can be either or both, depending on the forest-dependent species or function of interest. For example, some species will use the structure (e.g., big trees) no matter how old the forest is.[61,62] Other species have slow dispersal rates (many mosses and lichens) and the presence of suitable structure alone is not sufficient.[63] For slow dispersers, it takes time for the species to recolonize a stand.[64,65] In our study, we were focused on forest stands in terms of both structure and age—stands that are uncommon and becoming rare, regardless of what label different ecologists might assign them. For our purposes, the age/structure debate is a distraction from the important conservation discussion about how to keep these stands on the landscape.

Although we could use the LiDAR canopy height "signature" model to find LSOG forest by simple inspection in ARCGIS Pro, we wanted a more systematized process

Table 1. This study's forest classification system. The four classes were statistically distinguishable in terms of vegetation structure. See Figure 9 later in the report for details.

Class Name (code)		**Description**
Not Late-successional or old-growth classes (Not LSOG)		Not late-successional (LSOG) forest. Includes clearcuts, mid-age forest (~30-60 yrs old), and economically mature commercial forest (~60-100 years old).
Late-successional and old-growth classes (LSOG)	Transitioning Late-successional (Transitioning LS)	Forest generally past economic maturity, with a higher density of large trees, large snags, and fallen logs than Not LSOG stands reference above. Transitioning LS could be a Late-successional (LS) forest stand (see below) that has been recently partially-cut with a 20-30% canopy removal, but still containing significant late-successional qualities, or a commercially overmature stand that could become our LS class in the next 25-50 years. A sample of cored trees shows these stands had overstory trees that were generally 100-150 years old.
	Late-successional (LS)	Very high density of large trees and snags; large, downed logs, but not as many as true old-growth (see below). If there was evidence of harvesting, stumps were usually highly decayed and few in number, indicating a light harvest perhaps 50 years ago or more, and then probably only for the large spruce. A sample of cored trees shows these stands had overstory trees that were generally 150-200 years old, although older trees were sometimes present in the LS class.
	Old-growth (OG)	True old growth forest by our definition. No evidence or record of harvesting activity in the areas we sampled; no logging trails on 1960s aerial photos; high density of large trees and especially large, downed trees. Had forest dynamics of a steady-state forest with small to mid-size canopy gaps. No recent fire history. Big Reed Reserve was our primary source for OG "training" data.

Table 2. Eight canopy metrics derived from the LiDAR canopy height model. These eight metrics were calculated for each "training hectare" and for all hectares in the 4.2-million-hectare study area.

Canopy Metric	Description
Mean canopy height	The mean pixel height (of 10,000 1-m^2 pixels per hectare)
Maximum canopy height	The maximum pixel height (of 10,000 1-m^2 pixels her hectare)
95th percentile canopy height	The 95th percentile pixel height (of 10,000)
Canopy rugosity	The standard deviation of pixel (canopy) height (of 10,000 1-m^2 pixels her hectare)
Rumple index	A measure of canopy surface area divided by the ground surface area (ratio)
Cover fraction over 2m	The fraction of pixels over 2m in height within the hectare
Cover fraction over 6m	The fraction of pixels over 6m in height within the hectare
Cover fraction over 15m	The fraction of pixels over 15m in height within the hectare

for finding and quantifying LSOG forest for the large study area. To do this, we divided the study area into 1-ha units (~4.2 million units). Each hectare was comprised of 10,000 1x1 m data points (1 hectare=100x100 m). We generated eight descriptive canopy metrics (Table 2) for each of the 4.2 million hectares in the study area using the Tufts High Performance Computing Cluster.[66] These computations took about 36 hours of computing time to complete. The calculations could be done on a desktop computer or even a laptop but would have taken about 3 weeks of computing time. For more information on the rugosity and rumple metrics, see Reference 67 in the Endnotes.[67]

We then used random forest,[68,69,70] a classification algorithm, to classify each of the 4.2 million hectares into one of four categories: (1) Not LSOG, (2) Transitioning LS, (3) LS, and (4) Old-growth (Table 1). Although our primary interest was in the LS class, we provided training hectares for Transitioning LS, LS, and true OG, to see whether the random forest model could differentiate among these three LSOG classes based on the eight canopy metrics. We can readily distinguish among these classes in the field. To classify the entire study area, we needed known "training" hectares for the four forest classes in Table 1 so that random forest could try to extract statistical differences among the classes using the eight LiDAR metrics. We ran the random forest model 500 times, each time using a different random subset of the training data to build a single best differentiating model. This best model was then used to assign all the remaining hectares in the study area to one of the four forest classes, based on each hectare's eight canopy metrics.

For the training data, we used a combination of 361 hectares from our 2021-2022 bird study and an additional 102 hectares from Transitioning LS, LS, and true OG sites we surveyed throughout the unorganized territories in 2023 (n=463 total training hectares). Our training hectares included hardwood, softwood, and mixedwood forest of all ages, from clearcuts to true OG forest. However, we had relatively few true OG training hectares, which may explain why the model had difficulty distinguishing between LS and OG (see Results). We plan to address this issue with further research using a model including additional true OG training hectares and more LiDAR-derived metrics.

When in the field, we classified each training hectare as one of the four categories listed in Table 1. The field classification was based on observations at the site, including estimated time since harvesting, the presence or absence of early-successional, shade-intolerant tree species, the number of large-diameter trees in the overstory, the abundance of large snags and logs, and our overall impression of the forest stand. Our old-growth reference sites were from The Nature

Conservancy's 2,000-hectare (5,000-acre) Big Reed Forest Reserve in township T8R10, and another nearby 283 hectare (700-acre) old-growth tract. Accurate classification of the training hectares is critical to producing an accurate classification of the larger landscape using the random forest model. Our classification of a continuum of forest and structure into categorical bins is unavoidably subjective. Detailed ground vegetation surveys were conducted to support our field classification.

Ground-based vegetation data

At each of the 463 training-data hectares, we collected vegetation data to provide a more quantitative description of the forest LSOG classes. We used both 10x50 m vegetation plots and 10x100m plots, but all metrics were standardized for area sampled. The 10x50m plots were conducted for the "30-Year Bird Study" in the Moosehead Lake region in 2021 and 2022.[32] We added additional 10x100m plots from across the unorganized townships in 2023. We switched to the larger 10x100m plots in 2023 to reduce the variance among plots and to be more efficient in our sampling effort.

In each plot, we measured all living and dead trees ≥ 8 cm dbh. The species of each tree and its decay stage were recorded.[71] We also recorded the presence or absence of five late-successional indicator lichens and mosses.[72,73] We used a line transect method to estimate the volume of downed woody debris.[74]

Model validation

Random forest validates the model by using only 70% of the training data (selected at random) to build the model, and then classifies the remaining unused 30% of the training hectares using the model it generated. Random forest then compares its predictions to the true designation we gave the site in the field. Random forest repeats this process 500 times, each time randomly selecting a different 70% of the training data for building a model. The classification error rate of the unused 30% of hectares is then used to estimate the model's classification accuracy. This is the generally accepted approach to model validation. However, we went further. In 2024 we ground-truthed the model output by visiting not-previously-sampled hectares across the state to evaluate model predictions ourselves. This provided a more rigorous field evaluation of random forest that is seldom conducted.

Estimating LS Class rate of Loss

We estimated the rate of loss of LS class stands using annual updates of Global Forest Watch (GFW) forest change data. GFW categorizes 30x30 m pixels as having experienced forest loss, forest growth, or no change based on an analysis of yearly satellite imagery.[75] A pixel is categorized as forest loss (harvested) if >30% of the canopy has been removed. Because LiDAR was flown for most of the study area from 2015 to 2018, and the GFW data were available through 2023, we overlayed the GFW data onto our LSOG classification map to find LS stands that were harvested since the LiDAR was flown. Note that GFW does not tell us what kind of harvest has occurred. Some harvests, such as many on Bureau of Parks and Lands ownership, were too light to be detected by GFW and thus the true harvest rates of the LS class may be higher than we report.

Because the LiDAR for different regions of the study area were flown from 2015 to 2018, it was necessary to calculate annual harvest rates for each region and ownership type separately. We then calculated a weighted average annual rate of LS loss, where the weighting factor was the area of LS class contained in the within-year LiDAR set (i.e., set = year of acquisition).

Limitations

There are a few limitations to our assessment using LiDAR. First, we did not try to map stunted, high-elevation, old forest. Our interest in this study was in the "operational zone" managed for timber—areas with reasonably good soils and accessible to harvesting equipment, which is, by far, most of the study landscape. It is also the area most at risk for loss of LS class stands. We make no claims about mapping old, high-elevation forest in this study. Indeed, because of this, we masked out areas higher than 823 m (2,700 ft) in our analyses.[76] Our model also does not work as well with some areas mapped as wetlands (e.g., black spruce swamps or bogs) in the Maine wetland GIS data layer. However, we did include some LSOG stands as training hectares that were within the Maine GIS wetland data layer. A fertile area of future research would be to create a LiDAR-derived model for just old wetland forest that was trained on known LSOG sites verified by a forest ecologist. The random forest algorithm could likely locate wetland LSOG stands as well. All it needs is accurate training data. We also know old forest can be stunted (short) on poor soils, but our model used canopy metrics other than just height (see Table 2). We also need to better understand how steep, abrupt changes in elevation might affect the canopy metrics, because accurate and precise estimates of the ground elevation are key to generating the canopy height statistics.

Finally, because our model classified forest at the unit of a single hectare, we could miss small LSOG forest patches smaller than a hectare, and narrow "ribbons," such as riparian buffers. Our preliminary analyses of riparian buffers suggest that, while LSOG forest in buffers is important, it makes up a small proportion of the LSOG forest in the greater landscape.

Molly Taylor (left) and Ben Shamgochian (right) with a 202-year-old red spruce in an LS class stand (photo by J. Hagan)

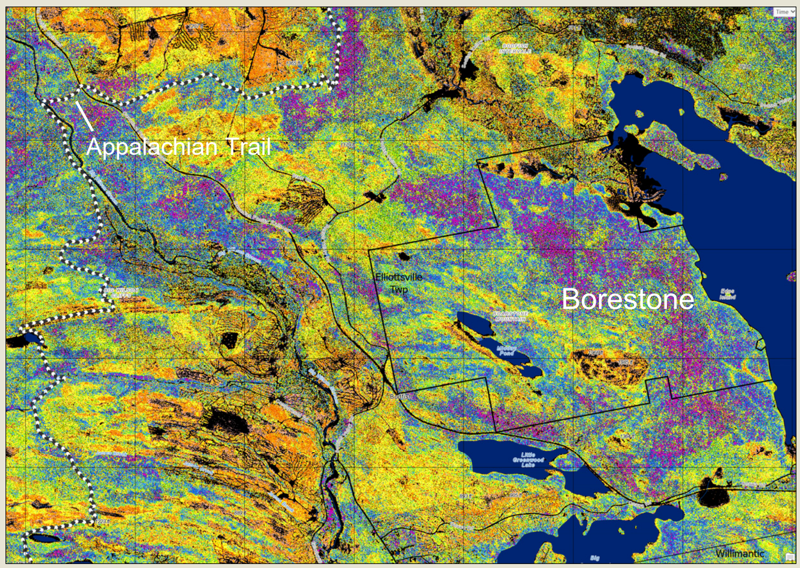
Results

Using eight canopy metrics (see Table 2) from the 463 known-class (see Table 1) hectares as training data, the random forest model classified the remaining roughly 4.2 million hectares within the area of interest. We inspected the model output for areas we knew to be LSOG forest but not used in the training data. This inspection indicated that the model was working well for discriminating Not LSOG from the three LSOG classes. A good example is Maine Audubon's Borestone Mountain Sanctuary, which is well known to contain substantial LSOG forest, but was not used as training data in the model (Fig. 5).

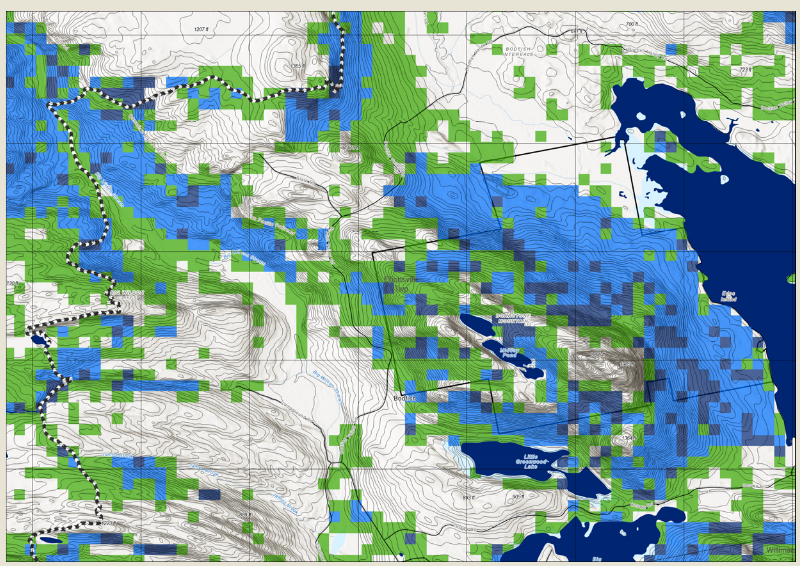
Key (meters)

- 0-2
- 2-4
- 4-6
- 6-8
- 8-10
- 10-12
- 12-14
- 14-16
- 16-18
- 18-20
- 20-22
- 22-24
- 24-26
- 26-28
- 28-30
- ≥30

(a)



(b)



Model Classification Key

- Not LSOG
- Trans LS
- LS
- "OG-like"

Figure 5 – (a) LiDAR canopy height model for the greater Borestone Mountain Sanctuary area. (b) random forest LSOG classification of each hectare in the same Borestone area. Note how the random forest classification aligns with the "blue-magenta" signature of the canopy height model. Grid=1 km^2.

Note that we refer to hectares classified as OG as "Old-growth-like." This is because the model was not very good at identifying true OG (see validation results below), but it was "seeing" something in the canopy structure data that looked like OG. We do not want readers to conclude that hectares classified as "OG-like" by the model are true OG. Before further evaluation of the results, let's look at the accuracy of the model output using two methods.

Validating the model classification

The most important result to report before further interpretation of the LiDAR-generated LSOG model relates to the *accuracy* of the random forest classification algorithm. We used two methods to validate the model results. Method 1 was the traditional internal validation of the model using the training hectares used by the model itself. Method 2 involved ground-truthing the model's output in the field.

Method 1 – Random forest (model) validation

Table 3a shows the model's accuracy in classifying "unused" training hectares into either Not LSOG or one of the three LSOG classes (refer to Table 1). The model has a 94.1% accuracy rate at correctly assigning a hectare to these two classes. The model validation indicates that if a hectare was classified into one of the 3 LSOG classes, it was indeed LSOG. What we conclude from this result is that any hectare classified into one of the three LSOG classes should probably be screened for late-successional or old-growth characteristics on the ground before making harvesting decisions.

Table 3b shows how the model classified hectares among the three LSOG classes. Not surprisingly, the model did less well here. But it still correctly classified Transitioning LS hectares and LS hectares correctly the vast majority of the time. It did not do a good job of correctly classifying the true OG hectares as "OG-like." We revisit how to improve old-growth classification in the Discussion.

Table 3a. Model validation results, Method 1 for Not LSOG vs. LSOG classification. Aid in interpretation: For example, of the 13+168=181 plots known to be in one of the LSOG classes based on classification in the field, 13 were misclassified by the model as Not LSOG.

		Class Predicted by Model	
		Not LSOG	LSOG
Actual Class	Not LSOG	268	14
	LSOG	13	168

Table 3b. Model validation results, Method 1 for the three LSOG classes. Aid in interpretation: For example, 9+69+1=79 plots known to be in the LS class based on classification in the field, 9 were incorrectly classified as Transitioning LS by the model, and 1 was misclassified as "old-growth-like."

		Class Predicted by Model		
		Transitioning LS	LS	"Old-growth-like"
Actual Class	Transitioning LS	61	10	1
	LS	9	69	1
	True Old-growth	4	8	5

Method 2 – Field validation

A complementary validation method is to ground-truth classified hectares that were not used as training data for the model. This is a more rigorous test of real-world performance because these "novel" hectares were not used to build the model, and may contain variability not captured by the training hectares.

While time and funding were limited for Method 2, we were able to visit 83 hectares in 2024 that were not used in building the model. Albeit limited, the results are still worth reporting.

Table 4a shows the results from field validation. Again, the model had a very high (92.8%) accuracy in correctly classifying a hectare as either Not LSOG or one of the three LSOG classes, which is very similar to the results of Validation Method 1 above. Table 4b shows the results for the three LSOG classes. Note that we did not have any true OG sites to sample for the field validation (hence 0's across the "True Old-growth" row). The model correctly classified Transitioning LS 78% of the time and LS 76% of the time. One of the reasons the field validation was not as good as in Method 1 was because field hectares sometimes fell on stand boundaries, and the model struggled to classify hectares split across stands. This is an understandable feature of the real world. Still, most of the time, the model correctly classified Transitioning LS and LS. This means that a forester could depend on the model being right most of the time. From our perspective, ground truthing of the model's classification will always be warranted before harvesting or conserving a

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Table 4a. Model validation results, Method 2 (field validation) for Not LSOG vs. LSOG classification. See captions in Table 3 for aid with interpretation.

		Class Predicted by Model	
		Not LSOG	LSOG
Actual Class	Not LSOG	19	1
	LSOG	5	58

Table 4b. Model validation results, Method 2 (field validation) for the three LSOG classes. We did not visit any true old-growth sites for the field validation. See captions in Table 3 for aid with interpretation.

		Class Predicted by Model		
		Transitioning LS	LS	"Old-growth-like"
Actual Class	Transitioning LS	14	4	2
	LS	12	25	1
	True Old-growth	0	0	0

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stand.

Summary of Validation Results

With the results of these two validation methods, we feel confident in the model and therefore estimates of the amounts of the four forest classes in the study area. Despite some false positives and false negatives, this model was 93% accurate in differentiating hectares between an LSOG condition and Not LSOG. Additionally, the model correctly classified hectares among the three LSOG classes at least 70% of the time, with true OG being an exception. Keep in mind that both Transitioning LS and LS hectares have high ecological value and are worth conserving, even though the LS class had a significantly higher density of late-successional characteristics than Transitioning LS, on average. Both Transitioning LS and LS have a significantly higher density of late-successional characteristics than the average forested hectare in the study area. While there is room to improve the model, it provides an extraordinarily cost-effective way to quantify LSOG forest in the unorganized townships in Maine, a task that was previously prohibitively expensive.

How was LSOG forest distributed among landowner types?

Given that the random forest model appeared surprisingly accurate in distinguishing Not LSOG forest from the three LSOG classes, we evaluated the amount and location of the forest classes across different forest ownership types. For example, we were able to estimate the amount of LSOG forest on public lands, private commercial forest ownerships, or even by watershed. Since we generated a single LSOG classification map for the entire study area, we can partition the map by any spatial unit of interest.

For this report, we assessed LSOG forest for six spatially explicit geographic areas:

1. Full 4.2M-ha study area (mixed private and public)
2. All private commercial timberlands (private)
3. All forests in a conservation easement (private)
4. Allagash River, entire watershed (mixed public and private)
5. Bureau of Parks and Lands (public)
6. Baxter State Park (public)

The entire land area of the study area was 4,186,196 hectares (10,339,904 acres). This excludes land above 823 meters (2700 feet) and tribal lands, for which LiDAR data were not available. Of the total area analyzed, 80.3% was Not LSOG, 15.9% was Transitioning LS, 3.0% was LS, and 0.9% was “old-growth-like” (Fig. 6).

Transitioning LS (green bars in Fig, 6) was a rather wide category on the ground. Some Transitioning LS stands did not yet have the structure of an LS forest, but still had considerable late-successional quality that was either just starting to develop, or residual quality after a light partial harvest (<30% removal) of an LS stand. The LS class (light blue bars) was the most consistently exceptional from a forest structure and age perspective. Often LS hectares were embedded in a larger area of Transitioning LS (see Fig. 5 for an example). Sometimes there would be predicted old-growth hectares mixed in with predicted LS hectares (also see Fig. 5).

Where there is a mixture of LS and “Old-growth-like” (dark blue bars) hectares, we recommend ground-truthing by ecologists to determine if the stand is true OG. As demonstrated with the validation results above, hectares classified as OG-like were not likely true old-growth. The random forest model was sometimes fooled into thinking a light partial cut was a true OG stand because the canopy was tall and canopy gaps of a light partial harvest mimicked the natural gaps of a true old-growth forest. We have plans to improve the model for identifying true OG.

We focused primarily on the LS class hectares because it is an increasingly uncommon forest age/structure class. Though not perfect, the random forest

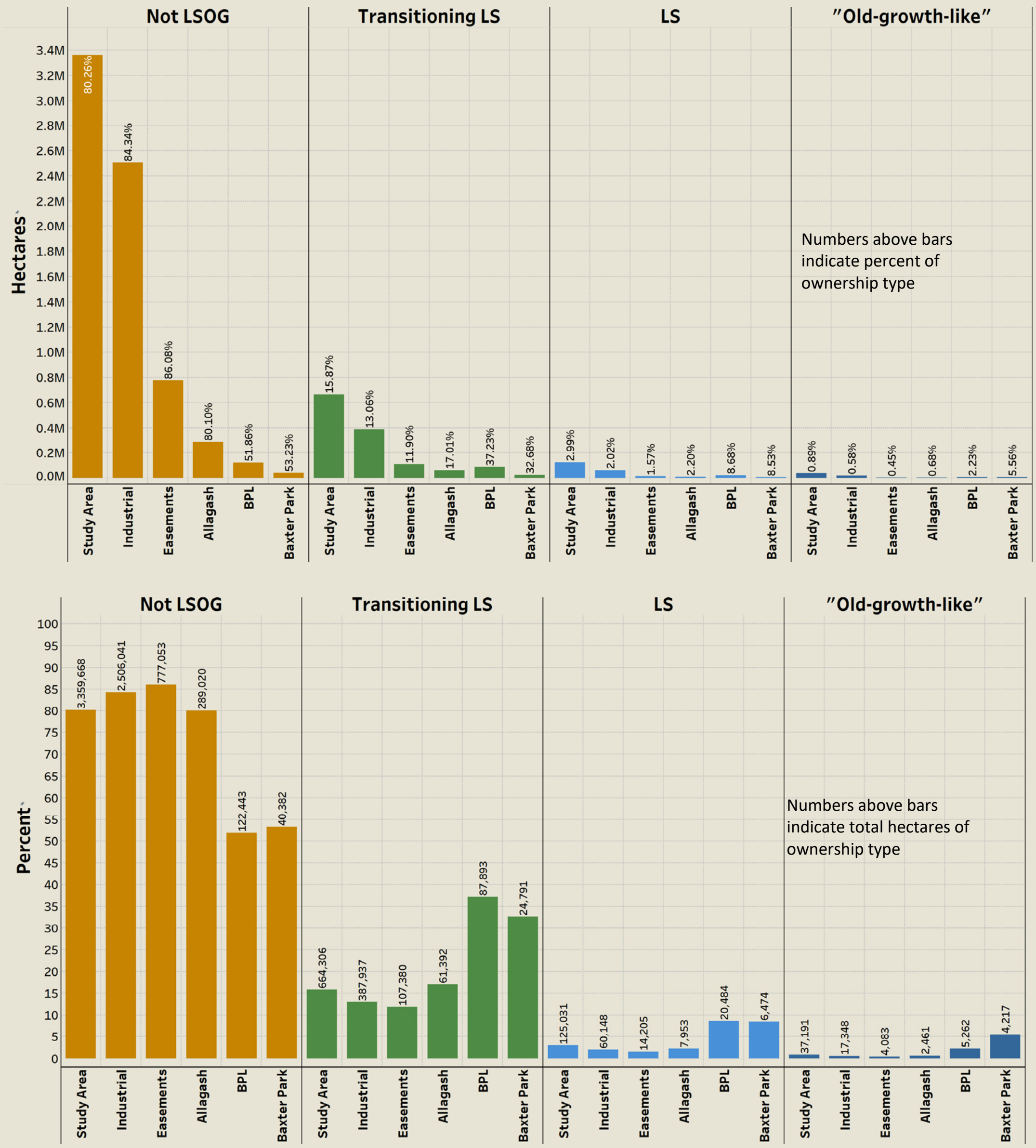


Figure 6 – (Top) total forest area in each of the forest ownership types, by forest class. (Bottom) The percentage of each ownership type by forest class. See Table 1 for definitions of forest classes. All area totals and percentages are restricted to the 4.2M hectare study area only.

algorithm was applied in the same way to every hectare in the entire study area—that is, the "yardstick" was identical. Therefore, we felt that it would be instructive to compare the amounts of LS class forest on different ownership types. Of any landowner type we analyzed within the study area, Bureau of Parks and Lands (BPL) lands had the highest percentage of LS forest (8.7%), reflecting the "lighter touch" of BPL forestry for the conservation of public values, including old forest conservation (Fig. 6).

By contrast, the private commercial landowners only had 2.0% LS forest. Of the 75,864 hectares of Baxter State Park, 8.5% was LS class, very similar to BPL lands. (NOTE: the northwestern township of Baxter State Park is allocated to experimental forestry, the Scientific Forest Management Area [SFMA], where some harvesting takes place). Conservation easements, which are mostly on commercial timberlands, only had 1.6% in the LS class. The Allagash River Watershed fared a little better, with 2.2% in LS, largely because of the BPL ownership embedded in the watershed. The same general pattern followed for the younger Transitioning LS class, except that there was a lot more Transitioning LS than LS (Fig. 6).

We can provide customized LSOG statistics and an LSOG map (GEOTIF or SHP file) to any landowner in the study area, upon request.[77]

These results lead to a logical question—'how much LSOG forest do we want or need in Maine, and how should it be distributed across the unorganized townships?' We revisit this question in the Discussion section.

We can provide customized LSOG statistics and an LSOG map (GEOTIF or SHP file) to any landowner in the study area, upon request.

How big (or small) are LSOG stands?

A logical question for conservation planners is 'how big are these LSOG parcels or stands?' The answer to this question might give planners useful information on where to focus land acquisition efforts if LSOG conservation is a goal. We plan to issue a follow-up report that focuses on our ideas for LSOG conservation prioritization. However, in this report we want to give readers some idea of how LSOG parcels are distributed in terms of area class (i.e., spatial extent of identified parcels).

Because our computer model classified every single hectare individually, irrespective of the forest class of surrounding hectares, we thought it would be more useful to conservation planners if we aggregated hectares into a simpler classification.

To that end, we did two analyses. First, we aggregated all LSOG classes (Transitioning LS, LS, and OG-like) into a single class for mapping and analysis of area class. We then analyzed the area class distribution of the resulting *aggregated* class. Figs. 7a and 7b show the aggregation graphically.

Second, to focus on just the two forest classes with a high density of late-successional features, we aggregated just the LS and "OG-like" classes into a single class, and deleted Transitioning LS hectares from the area-class analysis. Figs. 7a and 7c demonstrate this aggregation. We then analyzed the frequency distribution of the areas of the resulting parcels.

The statistical results of both aggregations, shown in Fig. 8, tell a complex conservation story. First, we see that in both methods there are thousands of small "gemstones" of LSOG forest throughout the study area. For example, there are 21,783 distinct parcels of LSOG in the 1-5 hectare class (the 3 classes combined, Fig. 8a), totaling some 58,621 total hectares in the study area. At the other end of the area spectrum, there were 386 distinct parcels greater than 250 hectares in the study area, totaling over 432,000 hectares (~1.1 million acres) (Fig. 8a). Of course, with our spatially explicit model, we know the location of each of these 386 parcels in the study landscape. This is new information for conservation planners and forest landowners.

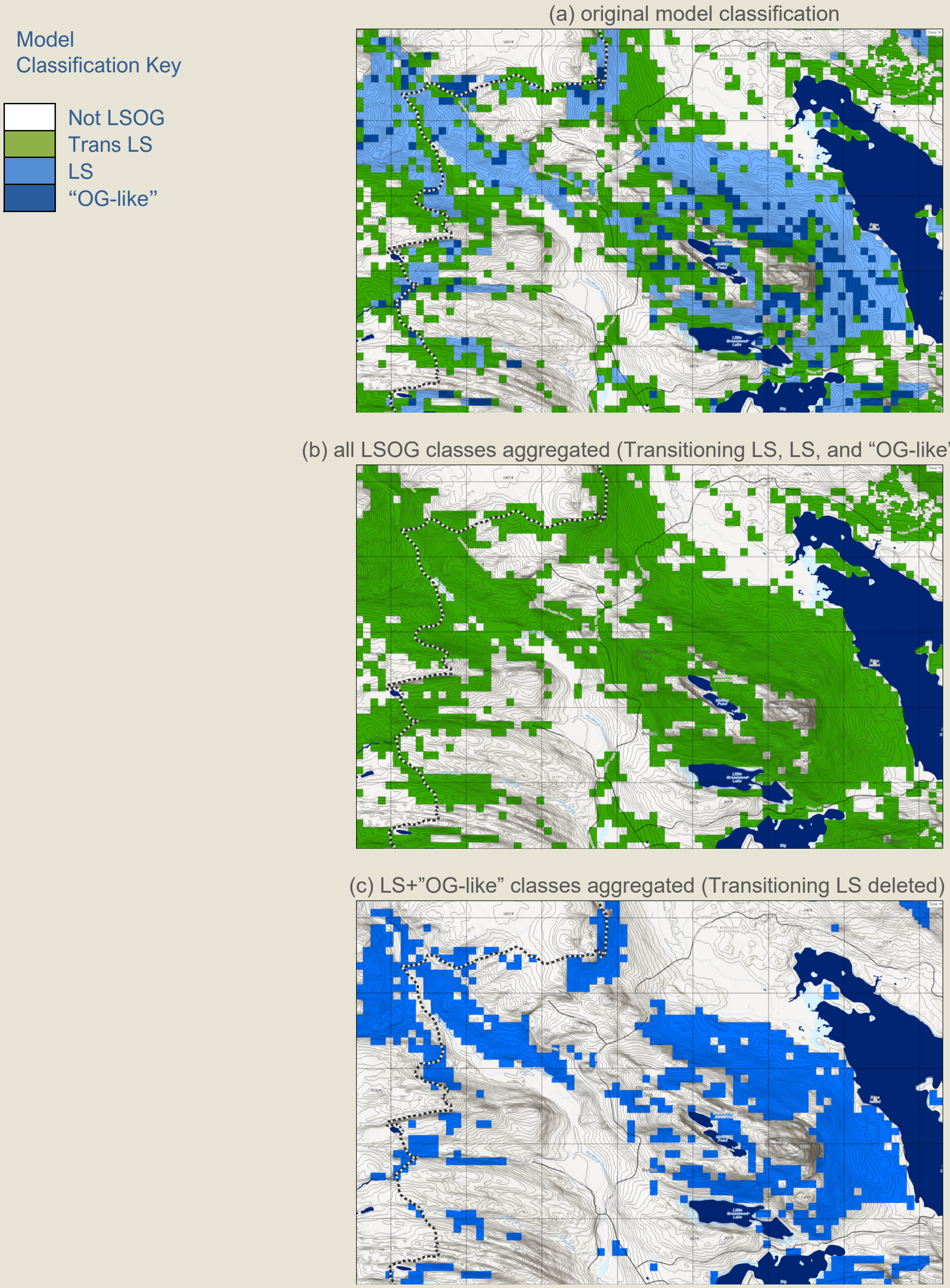


Figure 7 – How we aggregated classification boundaries to evaluate patch/stand area classes. (a) the original classification (same as Fig. 5b, the Borestone Mountain area); (b) reclassification by aggregating all Transitioning LS, LS, and "OG-like" hectares into a single class; (c) reclassification by aggregating just LS and "OG-like" hectares into a single class, and deleting Transitioning LS hectares. See Fig, 8 for resulting summary statistics for the entire study area. (Grid=1 km^2)

We can look at the same statistics for the LS+"OG-like" two-class aggregation, which highlights the more exceptional late-successional and "old-growth-like" parcels. In this aggregation, there were 10,021 parcels in the 1-5 hectare category, summing to 27,515 hectares in the study area (Fig. 8b). At the larger end of the area spectrum, there were only 45 parcels >250 hectares in extent, totaling 24,978 hectares (Fig. 8b).

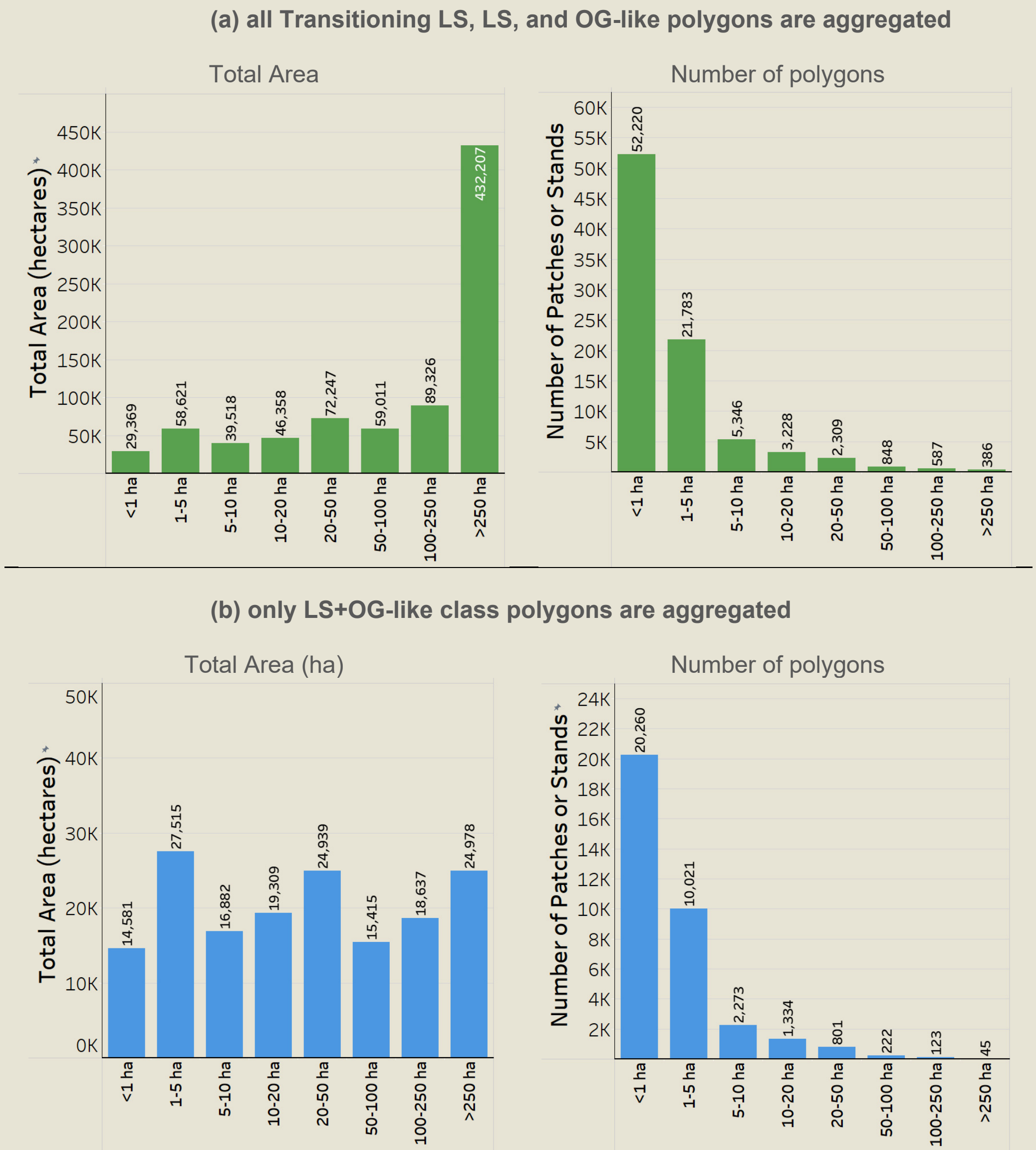


Figure 8 – The total area and number of polygons of LSOG patches or stands by area class. (a) All Transitioning LS, LS, and "OG-like polygons are aggregated into a single, combined forest class. (b) Only LS + "OG-like" patches are aggregated into a single, combined forest class.

This analysis highlights the need for at least two LSOG conservation approaches—one focused on the larger parcels and another focused on the smaller parcels. We make the case in the Discussion section below that it would be a conservation mistake to ignore the thousands of small remnants of LSOG forest, which can play a critical role in maintaining many late-successional species widely distributed throughout the study area. These small patches could also play a critical role in re-establishing slow-dispersing species into adjacent, regrowing forest. As important as the larger parcels are, so are the small patches from a species conservation perspective. We recognize that thousands of small patches might present a conservation planning challenge, but our model maps them all in a GIS system to their precise location, so it is easy to inventory and track them.

Ground vegetation structure and composition, by LSOG class

We generated an array of ground-based vegetation metrics derived from field data collected at each of the 463 training hectares to characterize stand structure of each LSOG class (Fig. 9). Different metrics functioned in different ways to distinguish among the four forest classes. For example, live tree basal area distinguished Not LSOG from the aggregate of Transitioning LS, LS, and true OG, but the three LSOG classes did not partition by live tree basal area (Fig. 9a). That is, live tree basal area would not be a good metric for distinguishing among Transitioning LS, LS, and true old-growth in our study area. By contrast, dead tree basal area nicely distinguished old-growth from other classes, but this metric was not different between Transitioning LS and LS hectares (Fig. 9b). Not LSOG had significantly lower dead tree basal area.

The density of large-diameter (≥ 40 cm [16"]) trees was the same in LS and OG, but higher than Transitioning LS (Fig. 9c). As expected, Not LSOG stands had a very low density of trees ≥ 40 cm dbh.

The proportion of total basal area in trees ≥ 40 cm dbh nicely separated among all four classes (Fig. 9e). Even though total live basal area was similar between LS and OG, a greater proportion of the basal area in OG stands was in larger trees.

The volume of coarse woody material was also significantly higher in OG than in all other classes, and it appeared to increase with stand age (Fig. 9f).

The quadratic mean dbh was higher for LS and OG than for the other classes, but not different between the two (Fig. 9g). By contrast, the coefficient of variation in dbh was higher in old-growth than in LS, but LS was not different from Transitioning LS (Fig. 9h).

To explore whether there were statistical differences among the four forest classes in "8-dimensional space" using all eight vegetation metrics simultaneously, we used Principal Components Analysis to generate a single derived metric (PCA 1) to capture this complexity. Fig. 9i shows PCA 1 scores for all four LSOG classes. PCA 1 shows clear separation among all four LSOG classes using the integrated information from all eight vegetation metrics.

All these metrics, including the PCA 1 score, suggest that our field assignment of the training data hectares indeed reflected real structural differences among the four LSOG classes, giving us confidence in our field classification of training hectares.

LiDAR variables by forest class

The logical follow-up question is whether our eight LiDAR-derived canopy metrics distinguished among the four forest classes (see Table 1) as well as ground-based vegetation metrics. Our two validation methods discussed previously already showed that LiDAR metrics alone can quite accurately classify "novel" hectares (hectares never visited for LSOG identification). However, inspecting each of the LiDAR variables might shed light on how these metrics work to distinguish LSOG classes. Recall that the eight canopy metrics are derived from 10,000 x (longitude), y (latitude), and z (canopy height) values at 1 m^2 resolution for every hectare. In Fig. 10. we show the statistics for the eight LiDAR metrics for the 463 training data hectares. As with the ground-based metrics, some LiDAR metrics distinguished among some of the LSOG classes but not others.

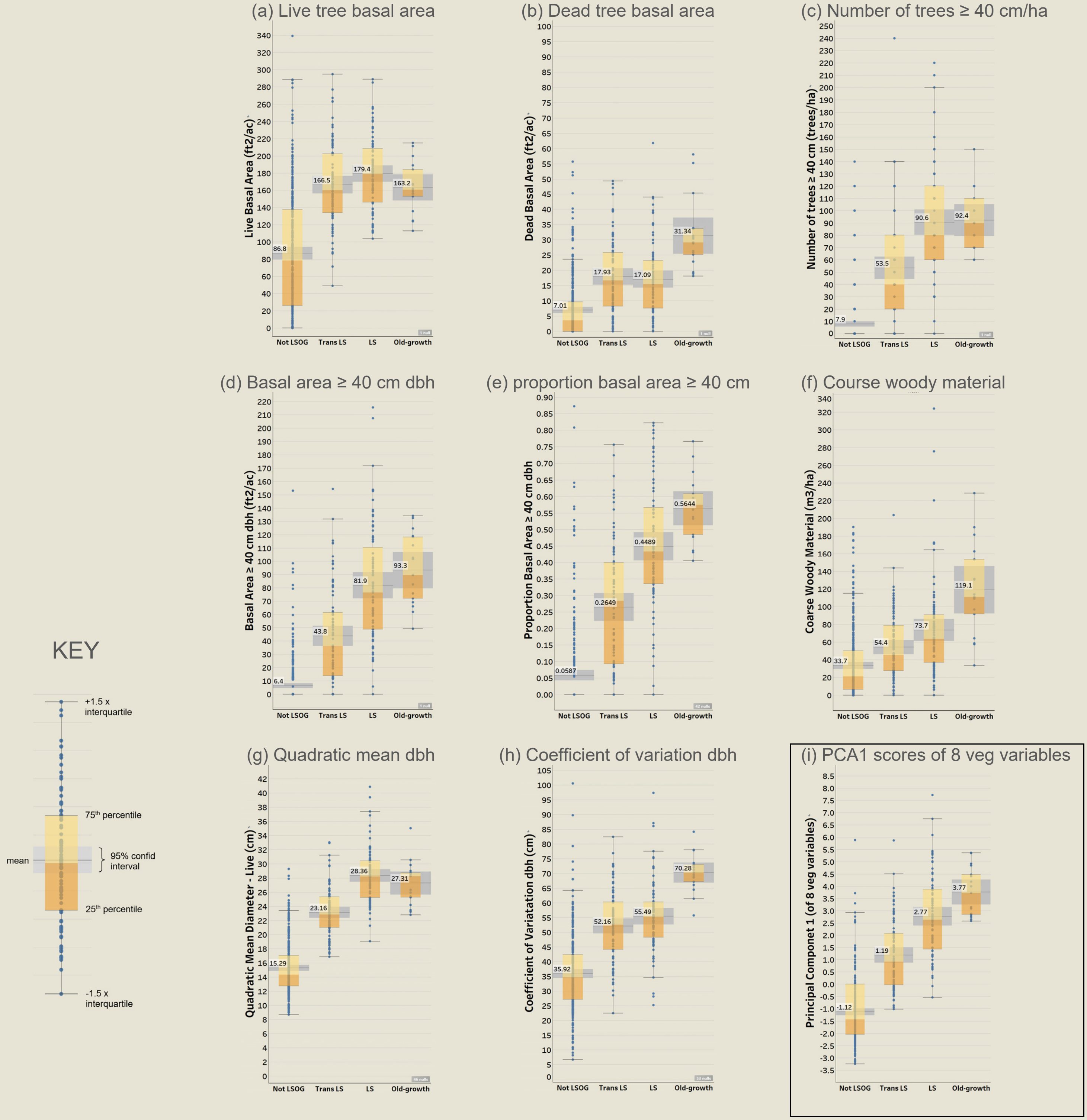


Figure 9 – Ground measurements of vegetation at the training data (known-class) sites across the four LSOG classes. Fig. 9(i) is a derived metric of variables (a) through (h) using Principal Components Analysis. That is, it shows how the four LSOG classes separate in 8-dimenensional space.

For example, the mean canopy height was slightly shorter in old-growth than in LS forest (Fig. 10a). This should not be surprising. True old-growth stands have natural tree-fall gaps that can result in a patchy, shorter forest at the scale of an individual large tree (e.g., a 20-30 m horizontal forest gap).

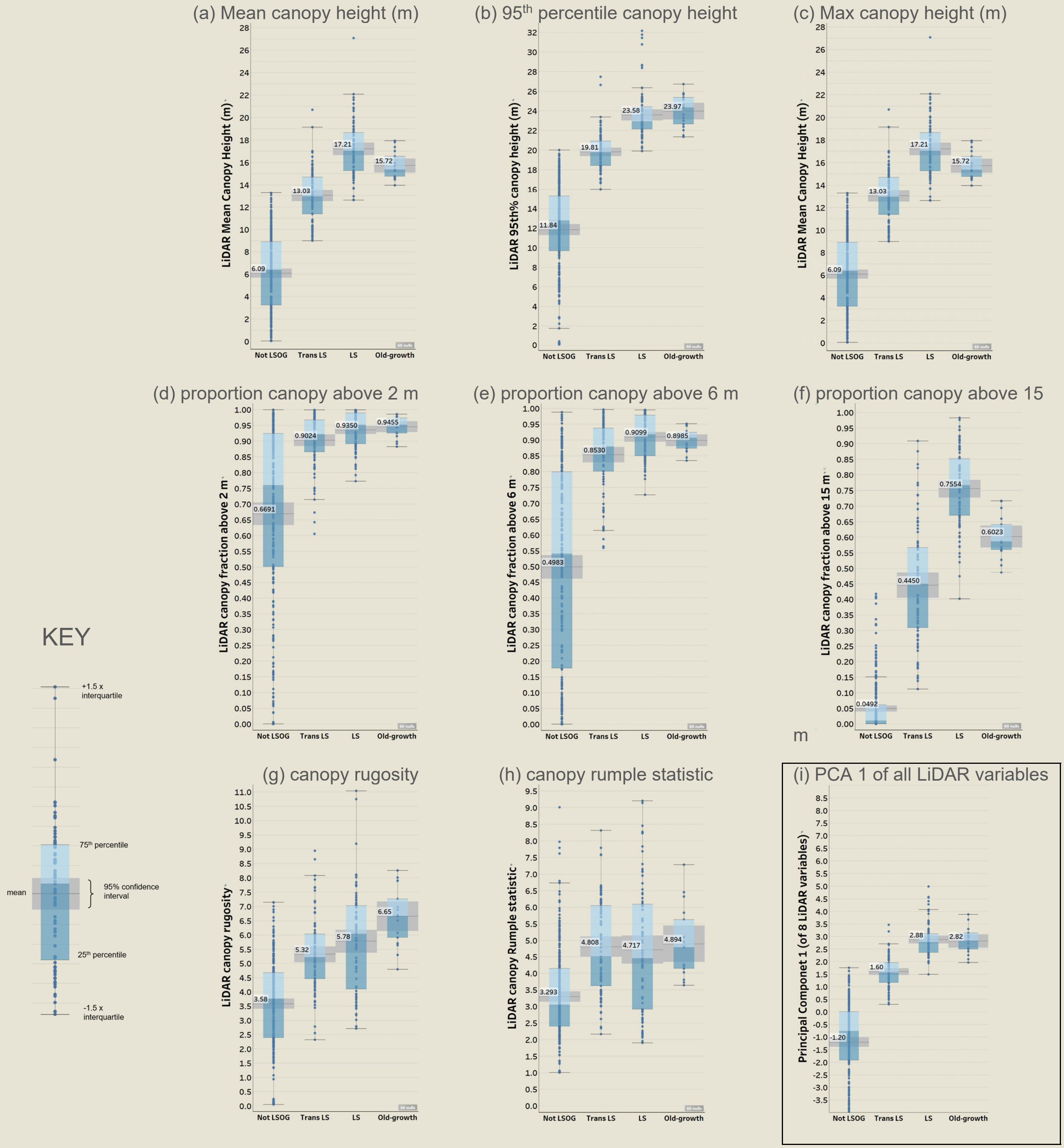


Figure 10 – Eight LiDAR metrics from training data (known-class) hectares across the four LSOG classes. Fig. 10(i) is a derived metric of variables (a) through (h) using Principal Components Analysis. It shows how the four LSOG classes separate in 8-dimensional space across the four LSOG classes.

The 95th percentile of canopy height was similar between LS and OG and significantly taller than in Transitioning LS (Fig. 10b). The maximum canopy height was also similar between LS and old-growth (Fig. 10c). The fraction of the canopy x, y, z coordinates above 2 m (Fig. 10d) and above 6 m (Fig. 10e) was similar among Transitioning LS, LS, and OG. This is because all three of these LSOG classes have most of the hectare's canopy above these two height categories. However, the fraction of the canopy above 15 m is much *lower* for OG than for LS (Fig. 10f). Again, this is because OG forest tends to have canopy gaps due to natural tree falls. Even though LS forest is old (150+), LS forest typically has not yet attained the natural forest dynamics of true old-growth.

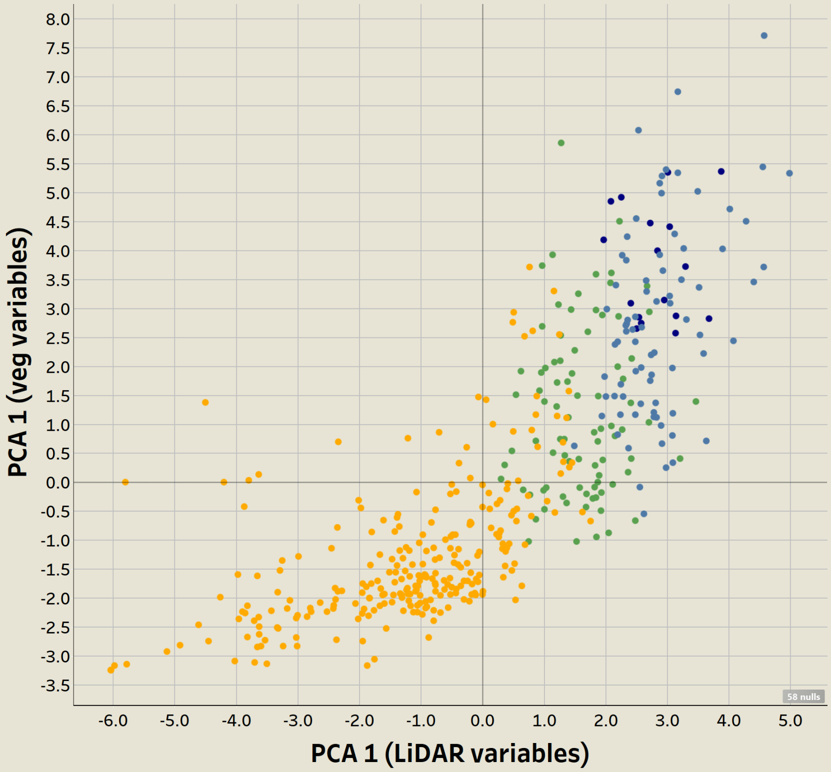
Of the two LiDAR metrics that represent canopy unevenness, canopy rugosity (Fig. 10g) increased as the forest aged (rugosity is a measure of the standard deviation of the 10,000 z [canopy height] coordinates for each hectare). The rumple statistic, which is the ratio of the surface area of the canopy to the surface area of the ground, did not distinguish among the three older forest classes. We expected this metric to behave the same as rugosity.

Finally, the first principal component derived from the eight LiDAR metrics separated Not LSOG and Transitioning LS from the older two classes, but struggled to differentiate between LS and OG (Fig. 10i). This explains why the random forest model, which is built on these eight metrics, struggled to distinguish between true old-growth and LS hectares.

Do ground-based vegetation metrics correlate with LiDAR-based canopy metrics?

We explored whether the eight LiDAR-derived metrics captured much of the same "information" about the hectare as the eight vegetation variables did using canonical correlation.[78,79] The model was highly significant (P<0.001), indicating that the LiDAR metrics were indeed capturing much of the information in the vegetation data. A graphical representation of this is shown in Fig. 11, which shows the first principal

Figure 11 – A plot of PCA 1 derived from the eight LiDAR metrics vs. PCA 1 derived from the eight vegetation metrics. The strong positive correlation indicates that the two datasets contained much of the same "information" about the training hectares.



component derived from the eight LiDAR metrics against the first principal component derived from the eight vegetation metrics. Though not perfect, the correlation is highly statistically significant (P<0.001).

Canopy height profiles derived from the LiDAR

Ecologists have long used vertical height profiles to describe forest structure.[80,81,82] Before LiDAR, generating vertical height profiles involved painstaking field work and typically resulted in increasing measurement error as the height of the canopy increased above the ground (above the observer). To further explore structural differences among the four forest classes, we used the "z" (canopy height) coordinate from the LiDAR to create a graphic that represented the height of the canopy surface (Fig. 12).

The canopy height profiles capture the structural evolution of the canopy surface as the forest ages. Not LSOG stands are comparatively short, as expected. The canopy surface increases in height through Transitioning LS, LS, and OG. Notice the true OG hectares start to take on a more sinuous shape. This is because of the development of natural tree-fall gaps associated with true old-growth, but which are not yet

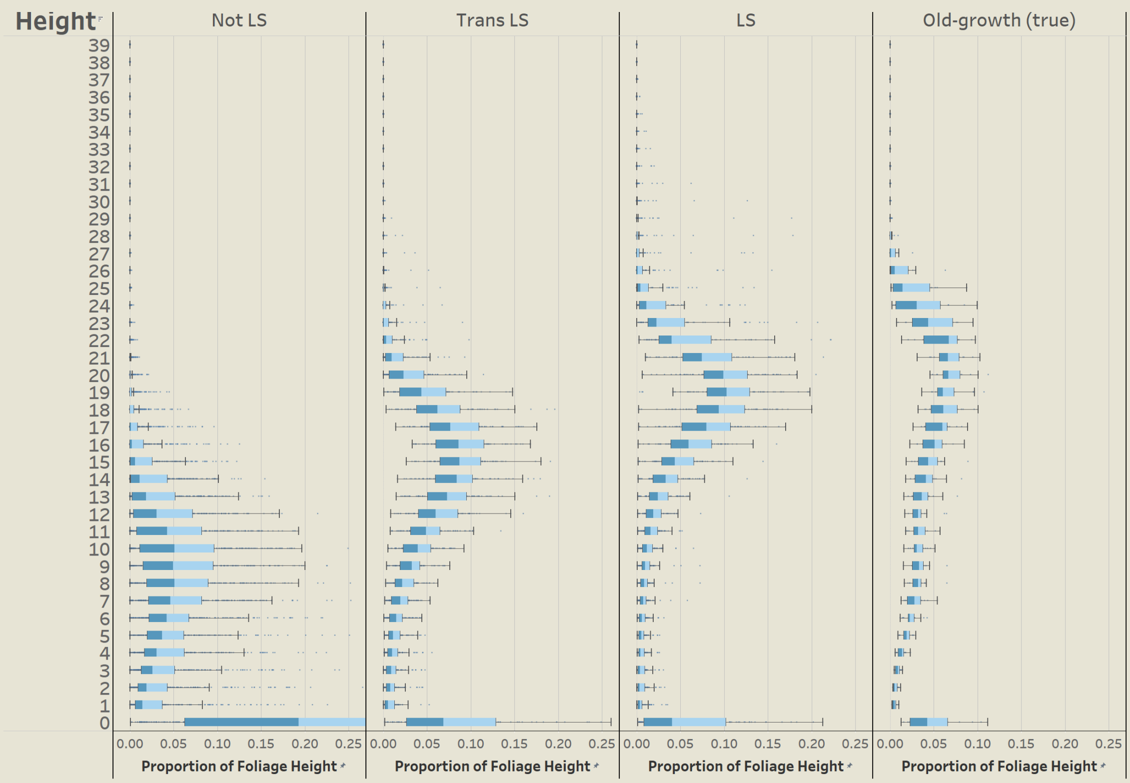


Figure 12. Canopy height (meters) profiles of the 463 training hectares. Each bar represents the proportion of the "z" (canopy height) coordinates in the specified height class (y-axis). The proportions were derived from the 10,000 z coordinates derived from LiDAR for each training hectare. Note the "S" shaped canopy height profile emerging in the true old-growth hectares.

developed into fully structural LS stands. In future work we plan to include metrics of the canopy profile in an effort to improve our discrimination of LS and OG forest.

How fast are we losing LS stands?

Based on Global Forest Watch forest change data through 2023, we estimate the rate of loss of LS forest to be -1.4% per year for the study area. Assuming all forest was treated the same, at that rate we would lose half of the remaining LS forest in 35 years (Table 5). Of course, different landowners have different management strategies.

To compare the rate of loss on public vs. private ownership, we calculated the rates separately for Bureau of Parks and Lands (public), Baxter State Park (public), and "industrial" commercial forest lands (private). We did not include private conservation working forest lands (e.g., TNC, AMC) in the "industrial" calculation.

Table 5. Estimates of the rate of loss of LS stands from selected ownership types. Half-lives are projections based on the rate of LS harvest over the past 6-8 years. Rates of loss are derived from Global Forest Watch data through 2023.

	LS Initial Hectares [1]	LS 2023 hectares	LS Annual Rate of Harvest	Half-life (years)[3]
Study Area	135,672	125,581	-1.40%	35.0
Maine BPL (Bureau of Parks and Lands)	21,135	20,523	-0.60%	96.1
Maine BPL (without Ecological Reserves)	17,381	16,388	-0.97%	48.2
Baxter State Park [2]	6,496	6,471	-0.02%	787.0
Large "industrial" forest owners	68,723	60,603	-2.16%	20.8

[1] year of initial LS estimate is 2016, 2017, or 2018, depending on the year in which the LiDAR was flown. Annual rates of harvest are adjusted for the number of years elapsed since the LiDAR for an area was flown.
[2] includes the Scientific Forest Management Area, which allows limited harvesting. Harvesting is not permitted in about 86% of the park.
[3] we calculated the first half-life of a zero-order rate of decay, which is appropriate for a fixed amount of "decay" regardless of the amount of LS forest remaining. That is, the amount of LS harvested each year is not likely dependent on the amount of remaining LS. The half-life starts in 2023.

The rate of existing LS loss on all BPL lands was -0.60% per year (Table 5). At this rate, half the remaining LS forest on BPL land would be lost in ~96 years. This calculation includes BPL's off-limits-to-harvesting ecological reserves. Prohibition of harvesting in the ecological reserves results in a lower overall rate-of-loss estimate for BPL lands. If we just consider harvestable areas of BPL ownership, rate-of-loss is about -0.97%/year, with a half-life of 48 years. By contrast, private industrial forestlands are losing LS at a rate of 2.2% per year, with a half-life of ~21 years (Table 5). That is, private industrial forests are losing LS stands at 3.6x the rate of public lands. This statistic highlights the urgency of developing LS conservation strategies for private commercial timberlands, especially since these lands contain most of the remaining LS forest (see Fig. 6). Note that our half-life estimates are based on harvest rates over the past 6-8 years. Our estimates assume the annual amount of LS harvested remains the same going forward. We have no way to predict future LS harvest rate other than to look backwards at the harvest data.

Because timber harvesting is only allowed in about 14% of Baxter State Park (the Scientific Forest Management Area, SFMA), the rate of LS loss for the whole park was only 0.02% per year, or a half-life of 787 years (Table 5). Therefore, more forest is probably entering the LS condition in Baxter than is being lost in the SFMA.

It's important to note we are not able to calculate hectares *entering* the LS class, although this will change soon (see Discussion: Future Research). Because harvesting is allowed on most BPL lands, new LS forest may be generated only in ecological reserves. Except in ecological reserves, existing LS hectares experience BPL's relatively light removals, dropping the LS stand to a Transitioning LS class in our classification system. It is unlikely that very many new LS hectares are being created on private commercial timberlands, although we know of exceptions to this statement on Baskahegan Co.'s ownership, which was heavily cut over in the first half of the 20th century, but has some significant LS stands today.[83]

The loss of LSOG forest to natural disturbances may also occur, but fine-scale (tree-scale) disturbance is a normal part of LSOG stand dynamics and would not take the stand out of an LSOG condition by our definition. By contrast, fire, ice storms, or budworm outbreaks could all take a stand out of an LSOG class. Some ecologists would consider those stands to still be LSOG, just with a different stand trajectory and history.

Molly Taylor preparing to sample an LS class hardwood stand (photo by J. Hagan)

Discussion

We have shown that publicly available LiDAR can precisely and accurately identify LSOG forest, remotely, with greater than 90% accuracy. This new knowledge creates an opportunity to have a social conversation about how much LSOG forest we, as a society, want, and how we want it distributed across a forested landscape.

How well did the LiDAR model find LSOG forest?

Our two validation methods, one computer-based and one field-based, showed the same result. The model could distinguish quite well between Not LSOG forest and LSOG with 94% accuracy. Keep in mind that we are trying to categorize something that is a continuum of multiple forest development pathways involving age and structure, which is inherently difficult to classify. The model was still good, but less accurate at distinguishing among the three LSOG categories (see Table 1)—Transitioning LS, LS, and OG.

Late-successional (LS class) forest was the primary age/structure class of interest in this study because of its high density of late-successional attributes, its relative intactness, and the fact that it is not yet exceedingly rare like true old-growth. LS stands in our classification do not have quite the density of late-successional features as does true old-growth, but they are still ecologically exceptional and disappearing. Our model did a very good job of finding LS class stands in the landscape.

Transitioning LS hectares exhibited a wider range of late-successional characteristics on the ground. Transitioning LS stands have the best chance of becoming LS forest in the next 25-50 years, or even recovering to a true old-growth condition in perhaps a century. Although less valuable in terms of the density of late-successional features, we recommend screening Transitioning LS stands to assess ecological value before harvesting them, especially given the rate of loss of LS stands.

The random forest model was not good at distinguishing true OG from the other two LSOG classes. This was partly because of the relatively few true OG training hectares on which we built the model. We plan to improve the classification algorithm for predicting OG with more training hectares, and a few new LiDAR-derived variables (see Future Research below).

Sometimes our model would classify 100-year-old aspen stands as LS. We found this to be true especially in Baxter Park. Bigtooth aspen, quaking aspen, and balsam poplar (all species in the genus *Populus*) colonize heavily disturbed areas, such as burned sites. Large areas of Baxter Park burned in the early 1900s. The aspen today are about 100 years old, and very tall. These old, burned stands are starting to “fall apart,” because the aspen have reached their natural life-span and are dying and falling over. Because of this, these old aspen stands have a lot of late-successional characteristics, including large living trees, large snags, and large logs. Aspen is even a common host for LS-indicator epiphytes (mosses and lichens).[84,85] These 100-year-old aspen stands make up a small percentage of the study area, but we are comfortable that they modeled as one of the three LSOG classes because of their relatively high density of late-successional characteristics. The University of

Maine is working on a species composition map of Maine that will soon allow us to distinguish between LS-aspen and LS-beech-birch-maple forest.[86]

While the random forest classification model using LiDAR-derived canopy metrics was surprisingly accurate, it is important to understand that it is not perfect. We found "false positives" (e.g., the model classified the hectare as LS but it was Transitioning LS). The model also had "false negatives," (it missed identifying a hectare as true LS (e.g., it classified a true LS hectare as Not LSOG).

However, LiDAR is a tool to screen vast areas of forest for late-successional characteristics. Ground-based surveys of an area as large as that investigated in this study would be prohibitively expensive. Although we are most confident in the LS class map, it is important to visit predicted LS class stands on the ground before making management decisions. The benefit of our model is that it shows a forester or conservationist where to look for likely LS stands. Depending on landowner goals and a field visit, management decisions can then be made for any given stand.

Our model was not built to identify stunted late-successional forest, such as cedar swamps or old high-elevation forest. In this study we were focused on the majority of the study area that is most at risk to harvesting. In "Future Research" below, we talk about how we could train the classification algorithm to find these forest types as well.

We encourage conservationists and researchers to "kick the tires" on the model output in the field. Upon request, we will provide readers with GEOTIFF model output. Display it in your GIS system and compare the modeled LS class map to late-successional stands you know from your own field work. The best evaluation is done in the woods; we welcome feedback from anyone who compares our maps to their own field knowledge. With your help, we can build an even more accurate model.

How much LS class forest exists, and where?

Altogether, for the 4.2-million-hectare study area, we estimated that about 20% was in one of the three LSOG classes (Transitioning LS, LS, and OG-like). Below, we focus primarily on the LS class because it was most accurately identified with LiDAR and because it is an uncommon and increasingly rare forest age class.

Only about 3.0% of the study area was in the LS class. The percentage of LS forest varied across the unorganized territories and by ownership types (e.g., public vs. private). Of the ~3.0% (125,031 hectares; 308,827 acres) of the study area that was in the LS class, 60,148 hectares (148,565 acres) were on private commercial timberland and 20,484 hectares (50,595 acres) were on Bureau of Parks and Lands ownership or in Baxter Park. So although BPL lands had a much higher proportion of LS class forest (8.7%), private commercial timberland had more *total* hectares of LS class forest because commercial forest makes up so much of the study area. This indicates that there is a big opportunity to conserve LS forest on private commercial timberlands.

There was more LS forest in the northern section of the unorganized territories than in the western or eastern sections. This may reflect the northern section's greater distance from mills and population centers.

Rate of LS loss

Our model predicted 125,581 hectares (310,185 acres) of LS class forest in the study area as of 2023, with an annual rate of loss of 1.40% per year. At this rate, half of the remaining LS forest would be lost in the next 35 years. This rate of loss is concerning from a conservation perspective because of the ecological importance of late-successional forest. The rate of loss was 3.6 times as fast on private commercial timberlands as on public lands.

Although public lands have a relatively high percentage of LS class forest, most of the remaining LS forest occurs on private commercial timberlands.

At recent rates of LS harvest, we can expect to lose half of the remaining LS forest on commercial timberlands in the next 21 years and on BPL lands in the next 96 years. The half-life statistic is a good "ruler" for showing relative rates of LS loss, but there will always be some pockets of LS forest that are inaccessible to harvesting equipment, or ribbons of late-successional trees in riparian buffers that are regulated. There are also some 266,642 hectares (658,607 acres) in the study area classified as "GAP 1" and "GAP 2," meaning they are off limits to future harvesting, such as public and private ecological reserves.[87] Although most of the area in GAP 1 and GAP 2 parcels are Not LSOG today, presumably they will be someday. Our report, and the new LiDAR-derived maps, should assist in a social conversation about how much LSOG forest "we" want, when we want it, and how we want it distributed.

Hopefully, public lands will continue to be a reservoir of LSOG forest. BPL harvests are usually lighter than those by private commercial landowners and BPL has an explicit goal of retaining important ecological values. BPL is more likely to partially cut LS class stands, dropping them to the Transitioning LS class, which often still has significant late-successional attributes. However, it is not clear that BPL is generating *new* LS stands, other than in its Ecological Reserves, which are off limits to harvesting. Once the partial-cut harvest regime is initiated, the plan is generally to partially harvest those stands again in 20-30 years, which would hold them indefinitely in the Transitioning LS class. To the extent LS class forest is a public value, we would caution against harvesting the increasingly rare LS class. At a minimum, BPL can use our LS maps to ground-truth LS stands that might then be conserved permanently. These LS stands have the best chance of returning to an old-growth condition in the next 50 years. Having said this, it is important to recognize BPL depends on timber sales for its annual budget, and its routine lighter harvesting approach is very good at retaining late-successional structure and composition in comparison to most private commercial timberlands.

Some private commercial landowners will apply BPL-type partial harvests to LS stands, if that is a viable economic treatment for the stand. LS stands on commercial timberlands are often a near-term target for harvesting because (1) there is a large volume of wood per hectare in LS stands, (2) large trees make for a more efficient harvest operation for the logger[88], and (3) commercial forest owners seek to convert these stands to a shorter and more financially lucrative harvest rotation. Sawmill technology has adapted to the generally smaller size of trees in the commercial forest today, so large trees are sometimes not as desirable—good news for large-tree conservation. Leaving stands in an LS condition, however, is an opportunity cost, unless a market for LS conservation develops (see "Strategies" discussion below).

On private commercial lands, we often found new logging roads to LS class stands, indicating impending harvest; or, they were just recently harvested. Figs. 13 and 14 show two examples of harvests of LS stands since the LiDAR was flown (2015-

2018). Usually, LS stands on private commercial timberland are converted to shorter-rotation stands through a 1- or 2-stage shelterwood harvest, resulting in a completely regenerated (i.e., young) stand (becoming 'Not LSOG' in our classification scheme). Or, LS stands are converted to a plantation in a single clearcut harvest. With regularly updated NAIP imagery and annual Global Forest Watch data, we will be able to monitor future loss of LS stands initially detected with this LiDAR-based LSOG mapping project.

Some LS stands are operationally difficult to get to. They may be, for example, above an abrupt slope that impedes access by harvesting equipment, on rocky post-glacial debris, or isolated by streams or wetlands. Stands that were inaccessible 50 years ago are more accessible with modern harvesting equipment and a more well-developed logging road network.

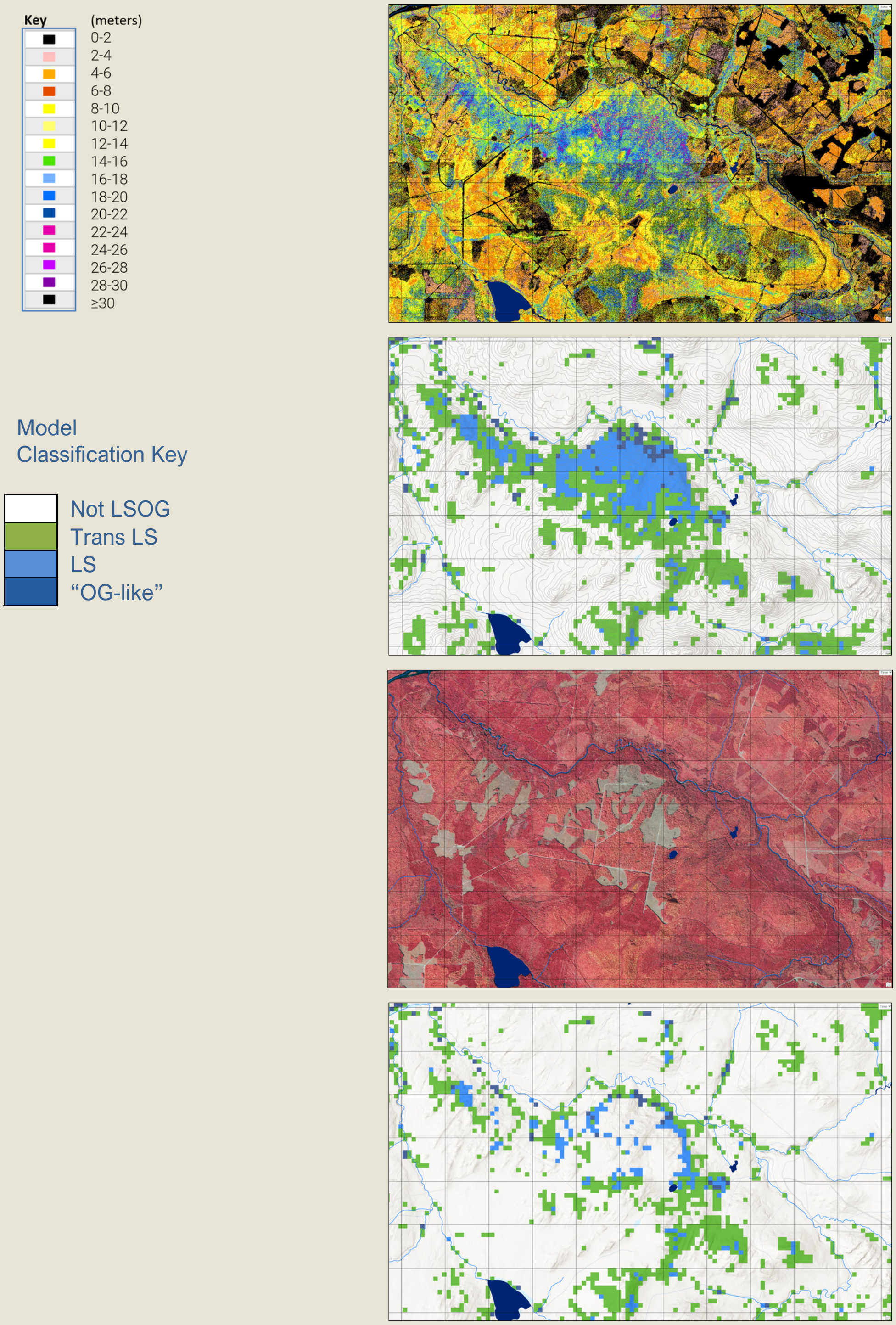
Some "ribbons" of LS forest will likely remain as long as landowners leave forested buffers along streams. However, these buffer strips can be partially harvested every 10 years. There is no guarantee stream buffers will continue to contain or generate late-successional characteristics over the long term. We have an ongoing study evaluating the late-successional value of riparian buffers. We often see ribbons of "blue-magenta" (likely LS in our canopy height symbology, e.g. Fig. 13) in the LiDAR signature along streams, but they are too narrow to be detected by our hectare-resolution model. Riparian buffers not only help keep water clean and cool, but they also contribute to late-successional structure and function across the larger landscape.[89,90,91] Nevertheless, in our view, given the increasing rarity of LS stands, retention of riparian buffers should not be in lieu of conserving other remaining LS stands.

We had no way in this study to estimate the amount and rate of forest growing into an LS condition. We will, if LiDAR is flown again or if we can use NAIP imagery for generating a canopy height model in the future. However, keep in mind that stands move into an LS condition slowly, over decades, whereas they come out of an LS class instantaneously when harvested, even if lightly harvested. Except for the portions of the study area off limits to harvesting (e.g., public and private ecological reserves [~71,000 hectares, 175,000 acres],[92] Baxter State Park [73,248 hectares, 180,925 acres, excluding the Scientific Forest Management Area], and Katahdin Woods and Waters National Monument [35,851 hectares, 88,554 acres]). It is unlikely that new LS forest is being generated in significant amounts relative to what is being lost in the 4.2-million-hectare study area.

Conservation Implications: How much LS class forest do we want, and how should it be distributed?

At least for now, this is a social question, not a scientific one.[93,94] Are we satisfied with LS forest ultimately remaining only on our public lands (e.g., BPL, Baxter State Park, Katahdin Woods and Waters Monument) and private conservation lands (e.g., TNC, AMC, Northeast Wilderness Trust)? Do we write off LS forest on most of the unorganized townships?

In our view, restricting LS forest conservation to only public lands and private conservation NGO lands would be a risky venture from a species conservation perspective. LS is an age/structure class of forest that represents only 3% of the study area today—a forest type that once made up 70% or more of the study area.[28]



(a) canopy height model (based on 2018 LiDAR data)

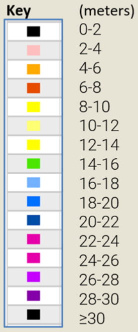
(b) Random forest classification of the forest in (a) above. Blue represents LS forest, green represents Transitioning LS, and magenta indicates “old-growth-like” forest.

(c) NAIP aerial imagery, 2023; grayish areas are new white spruce plantations.

(d) Random forest model from (b) after deleting harvested areas

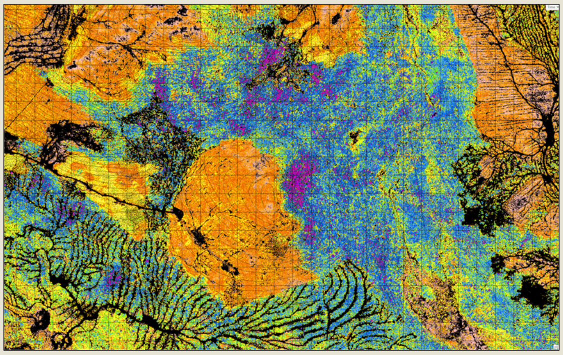
Figure 13 – An example of LS class stands being harvested since the LiDAR was flown for this scene in 2018. (a) note the blue-magenta canopy height “signature” suggesting LS forest. (b) the classification of the forest based on LiDAR in (a). (c) NAIP aerial imagery from 2023 showing clearcuts in the blue LS stands. (d) the modeled landscape after harvested areas are removed. Most of the LS stands were converted to white spruce plantations. The grid scale in each scene is 1x1 km.

The challenge is that most of the remaining LS forest in our study region is on private commercial timberlands. As shown by our analyses, LS forest is also being cut at a relatively high rate on private commercial timberlands. Once LS stands are lost, they are lost for a very long time—150 years at a minimum, but more likely hundreds of years. It would take a very long time to “rebuild” a late-successional stand with large trees, large dead trees, and large logs on the forest floor. And even

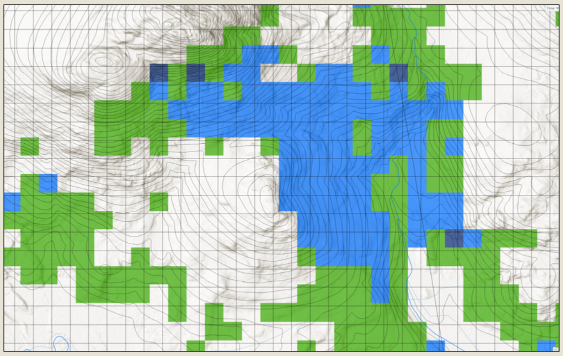


Model Classification Key

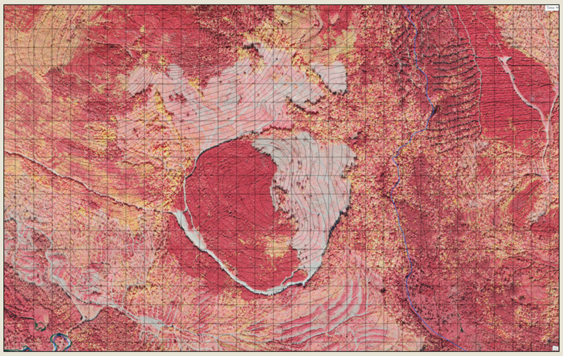
- Not LSOG
- Trans LS
- LS
- “OG-like”



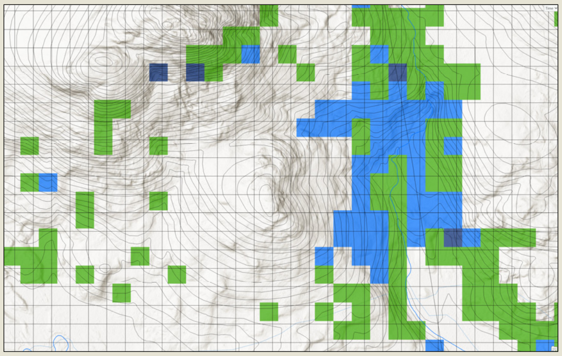
(a) canopy height model (based on 2016 LiDAR data)



(b) Random forest classification of the forest in (a) above. Blue represents LS forest, green represents Transitioning LS, and magenta indicates “old-growth-like” forest.



(c) NAIP aerial imagery, 2023; light areas are new clearcuts.



(d) Random forest model from (b) after deleting harvested areas

Figure 14 – Another example an LS class stand that has been harvested since the LiDAR was flown (in 2016 for this scene). The grid scale in each scene is 1 hectare.

then, species that prefer older forest would have to find their way to it. *Why not conserve what still exists today?* This would be more cost effective and produce a better conservation outcome.

Unfortunately, we have no existing institutional mechanisms tailored to conserving LS forest on private timberlands. Most conservation easements are buying development rights, not timber rights, and historically have said little or nothing about retaining LS forest. This is changing as the conservation easement strategy has matured over time. Often easements require landowners to be sustainably certified, but neither of the two main certification systems, SFI[95] and FSC[96], require protecting these remaining LS forest stands. We hope this report will help change that, because now we know how much there is and where it is.

Why not conserve what still exists today? This would be more cost effective and produce a better conservation outcome.

Often, we have heard from our conservation colleagues that these LS stands are too small to be ecologically significant. Conventional wisdom in the conservation community is that bigger is always better. Empirical support for this theoretical dogma is lacking and inconsistent.[97] In addition, at present there are literally thousands of LS class stands, some small, some large, somewhat well distributed across the study area. These stands, if conserved, can function as refugia for many species that are sensitive to forest age and/or structure. If conserved, they have the potential to act as population sources for the surrounding landscape someday. If conserved, they can keep species well distributed across the entire study area.[98,99,100,101,102,103,104] If ignored, we will likely lose certain species over vast areas of the landscape over the next century.

In our view, we can do both— conserve large landscapes, even if cut-over, because they can regrow if allowed to, *and* conserve the LS ecological "gemstones" that still exist widely across the working forest landscape today. It would be a conservation mistake to ignore or dismiss the ecological importance of small stands or patches of LS forest for maintaining healthy biodiversity across the study area. To the question "what is the smallest size of a late-successional stand that has conservation value?", eminent conservation biologist and Mainer Mac Hunter says "A single tree!".[105]

LSOG conservation strategies

In 2004, Hagan and Whitman[106] laid out multiple strategies for conserving LSOG forest. These strategies are as relevant today as they were in 2004. At the time, some landowners voluntarily elected to screen stands before harvest with a simple LSOG field survey.[107] A lot of LS forest has been lost since 2004, but we have a second chance. We hope our new method for mapping LSOG will encourage the conservation strategies below.

1. Acquire more conservation land: A bright spot for LSOG conservation has been private conservation organization purchases of timberland in the last 20 years. For example, The Nature Conservancy of Maine now owns some 65,590 hectares (162,000 acres) in the St. John watershed that was formerly private commercial timberland. The Appalachian Mountain Club owns about 52,000 hectares (128,000 acres) of former commercial forestland east of Moosehead Lake. These two conservation organizations still harvest timber, but conservation is a prime directive. AMC, for example, set aside a large portion of its ownership as an ecological reserve that contains an exceptional LS stand, which we used as "training data" for building our LSOG model. One of AMC's goals is to restore the landscape to a late-successional condition.[108] This is a very different forest trajectory than under the previous private commercial landowner.

   Over the past 40 years there have also been significant public forestland acquisitions.[87] For example, since inception in 1987, the Land for Maine's Future program has helped conserve 255,000 hectares (630,000 acres) as in-fee purchases or easements.[109] The point is, we have well established instruments for land conservation that can be employed to target LSOG conservation.

We are sensitive to the fact that adding more conservation land off-limits to harvesting could constrain the forest products economy. To avoid an impact on wood supply, we would cut different wood, not necessarily less wood. In seeking biodiversity gains through acquisitions, conservationists need to consider socioeconomic impacts. LSOG conservation does not have to be at the expense of people's livelihoods.

2

"Precision" conservation easements: Given that we now know where LS stands are, we could adapt the conservation easement mechanism that has been used and perfected to conserve working forest in Maine over the last 25 years. In the case of LS conservation, however, payments could go to landowners to forgo harvesting in LS stands, either for a period of time (a "term" easement) or in-perpetuity. The appraisal value would be derived from the current stumpage value of the standing timber in the LS stands.

Monitoring would be relatively simple. Regularly flown NAIP imagery would readily show any harvesting that takes place in the LS stand. Most harvesting is also detected by the Global Forest Watch program. Eased LS stands would be entered into landowner and land trust GIS systems, easily tracked, and designated as off-limits to harvesting. Conservation at the stand scale might seem painstaking, but it is not with a GIS system, which all commercial landowners have. Perhaps LS easement holders would do a field visit to eased LS stands every 5 years, but otherwise monitor with annual Global Forest Watch data and NAIP imagery, both of which are publicly available. A conservation "market" for LS stands would also give landowners pause before cutting them. The Forest Society of Maine has been exploring this type of "precision" easement.

So far, public input to the SFI or FSC certification standards has not insisted on the conservation of LS class stands.

At a minimum, prospective conservation easements can now be screened for LSOG forest. With this knowledge, easement negotiations can more confidently take into account LSOG forest values and goals.

3

Strengthen forest certification standards: In our view, forest certification programs should not allow harvesting of LS stands, which make up only 3% of the landscape, and more like 1-2% on most private commercial timberlands. The standards for both SFI and FSC are revised on a regular basis (~ every 5 years) and incorporate public input. So far, public input to the SFI and FSC standards has not insisted on the conservation of LS stands. FSC has a "Type 2" old-growth category in its standard that seems to align with our LS stand definition.[96] However, FSC does not say how much Type 2 forest should be retained. The SFI standard has language about "forests with exceptional conservation values."[95] As ecologists, we would call LS stands in the unorganized townships of Maine "forest of exceptional conservation value."

4

LSOG Forest Carbon Offsets: We are not proponents of forest carbon offset projects that are weak on the "additionality" and "leakage" issues, meaning someone's carbon emission is not really offset.[110,111] For example, if we paid landowners for the standing carbon in an LS stand, we might save that carbon *in that stand*, but the landowner would likely cut the equivalent amount of wood elsewhere, or some other entity would (termed "market leakage"). We would have achieved an LS conservation goal, but not the carbon goal, which is the whole point of carbon offsets.

However, what if landowners are paid for carbon in the LS stand and are required to use the proceeds to invest in silviculture that *accelerates* growth of other areas of their ownership? Then, new carbon would be stored that would not have otherwise been stored. This addresses both the additionality and leakage issues. This would generate new "real" carbon storage AND achieve an ecological conservation goal at the same time. Several conservation groups are exploring this potential instrument, including the New England Forestry Foundation's Climate Smart Commodities program.[112]

5

Incentives: Maine already has a Tree Growth Tax law that gives forest landowners a tax break for lands with a forest management plan.[113] Landowners could be given an additional tax break for acres that are maintained as LS forest. (We acknowledge there is strong political opposition to *any* change in the Maine Tree Growth Tax law, even if it financially benefited landowners.)

Alternatively, a federal or state incentive fund could be established to pay landowners for not cutting certain acres. Such a fund might require 10-year commitments *not* to harvest, and pay a higher amount per acre for in-perpetuity commitments not to harvest. This type of program already exists at the federal level—the Conservation Reserve Program (CRP). Within this program is a Forest Management Incentive (FMI) option.[114] Conserving or creating "upland wildlife habitat" is one of the sanctioned practices of the FMI program. It seems that conservation of LS forest would be aligned. The program explicitly pays landowners for creation of early-successional habitat but not for conserving late-successional habitat. Payments for FMI are limited to $200,000/landowner, and designed for small woodlot owners. But given President Biden's 2022 Executive Order to inventory the nation's mature and old-growth forests, it might be a good idea to modify CRP/FMI funds to support conservation of LS stands on larger commercial forest ownerships where there is an opportunity to scale up conservation impact.

6

Stand management to retain and promote old structure: While the previous strategies focus on the conservation of existing late-successional forests, a complementary strategy is to encourage the retention of, and future development of, late-successional forest attributes through forestry. With careful attention to existing late-successional features, foresters and loggers could harvest wood while retaining the maximum possible number of large trees, snags, and logs, and even accelerate the development of these same features through silviculture.[115,116,117] The general goal is to simulate the processes of tree mortality, gap creation, and heterogeneity of old forests by using precise and limited harvesting, girdling, and retention of legacy trees.[118]

We hope readers of this report will adopt or adapt one or more of these strategies, or come up with other ideas for LSOG conservation not mentioned here. We stand ready to help landowners and the land conservation community conserve LSOG forest in Maine.

Future Research

Finding small patches and riparian "ribbons" of LSOG forest

The hectare-scale classification of our study area is useful for stand-level management and conservation, but it misses small LSOG patches (less than a hectare) and "ribbons" of LSOG forest along narrow riparian buffers. Most riparian buffers are 75' (23 m) on either side of the stream bank. Such buffers are too small for our modeling approach to detect. However, we have tested a finer scale model at 0.25-hectare resolution on a few townships. This more fine-grained model did pick up more LSOG forest in riparian buffer strips, but the amounts gained were small in proportion to LSOG stands in most townships. However, this preliminary result should not diminish the potential importance of riparian buffers for LSOG value. In fact, because of the long, linear nature of riparian buffers, they could play a disproportionately important role (relative to their area) in keeping LSOG characteristics well-distributed across the study area.[119] Our ongoing research is addressing this question.

Finding true old-growth

We are only scratching the surface of the capacity of LiDAR data to tell us about ecological attributes of the forest that previously could only be obtained by field visits. In some cases, LiDAR can even tell us *more* about forest structure than do on-site visits. For example, it is very difficult to quantify canopy structure in the field, or to generate canopy height profiles with such thoroughness and precision as shown in Fig. 12.

Although our selected LiDAR metrics did a poorer job of distinguishing LS forest from true OG, we believe we can build a model that can differentiate between the two. This matters because we found a 283-hecare (700-acre) tract of "blue-magenta" true old-growth during this study that the conservation community did not seem to know about. If we can build a computer model to find true old-growth, we might find more, yet unknown, true old-growth stands. Four million hectares is a lot of area to screen for old-growth forest. That we found the 283-hectare tract mentioned above justifies this exploratory research. There may be more true old-growth than we think.

Two data sources give us optimism for finding true OG using publicly available LiDAR. In our modeling to date, we used only the canopy surface model generated from LiDAR. The canopy surface model uses only about 10% of the LiDAR data. If we used the full LiDAR 3-D point cloud, we may be better able to distinguish OG from LS. Consider Fig. 15, a 10x100m slice of 3-D LiDAR data from an exceptional LS stand on BPL land in Deboullie Township, and a 10x100m slice of LiDAR data from Big Reed, true OG. The cross sections look quite different, even though both forests are of extraordinary conservation value. If we use the full 3-D point cloud, we

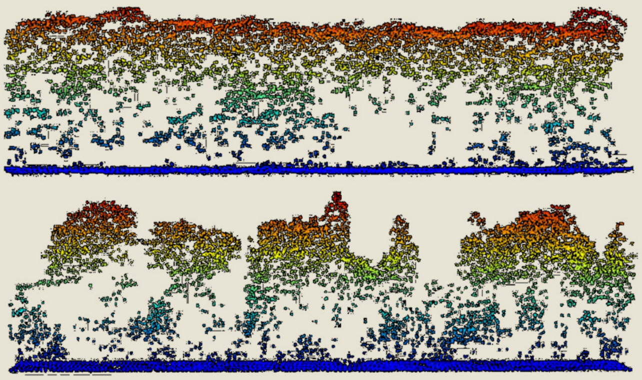


Figure 15 – Cross section of 100 m of LiDAR data from (a) a late-successional stand (~150 years old), and (b) a true old-growth stand (250+ years old). Both stands are of exceptional ecological value. But note the structural difference between the true old-growth and the late-successional stand. In the old-growth stand, natural tree-falls due to old age create an uneven forest canopy. Late-successional stands have not yet acquired the ecological dynamics of true old-growth. We will explore whether we can use this distinctive LiDAR "signature" to find currently unknown old-growth stands in Maine.

can likely extract LiDAR metrics that will distinguish between these two cross sections. It will require a more powerful computer, or more computer time, to process the full 3-D point cloud for this purpose.

In addition to the full 3-D cross section described above, we have explored whether we can "see" large, downed logs in the full 3-D LiDAR data. Large, downed logs are probably the single most obvious indicator of true old-growth forest, based on our extensive field work in both LS and OG stands, and the work of others.[120,121] Fig. 16 shows only LiDAR points between 0.2 and 2.0 m above the ground surface. Curious linear features are clearly revealed. In a follow-up field visit to this specific hectare in Big Reed Reserve, we verified that the linear features in the LiDAR image are indeed large downed logs. LiDAR even depicts the orientation and length of the downed log accurately. Our field visit indicated that the publicly available LiDAR we used could only reliably detect large downed logs (~40+ cm in diameter). But that is good enough for our purposes; it is the density of *large* downed logs that indicate true old growth. Anecdotal comparison of LiDAR scenes from LS forest showed a much lower density of large logs. Thus, adding the density of large downed logs as detected with LiDAR to our existing 8 canopy metrics could significantly improve LiDAR's ability to distinguish LS from true OG stands. We are working to build a model that includes these 3-D structural elements.

Finding old-growth forested wetlands

As stated earlier, our model was not designed to identify stunted old black spruce wetlands and cedar swamps, or high-elevation old spruce. However, there is no reason our same modeling approach cannot be used to locate and map these forest types as well. The key to success is having known "training" hectares of whatever forest type is of interest. We can then train the computer to find more hectares that have the same LiDAR signature, especially when combined with hydrology maps. We hope to use this approach to find old cedar forests in the near future, using known training hectares provided by foresters and ecologists. We encourage other

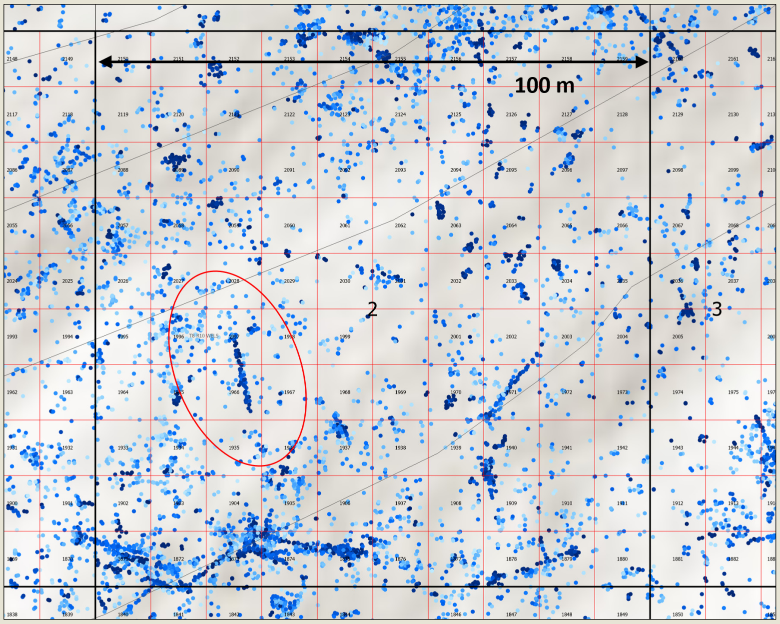


Figure 16 – LiDAR 3-D points between 0m and 2m above ground from a hectare in Big Reed, a true old-growth site. The red grid is 10x10m. The red circle identifies one of many downed logs in the scene. Linear features represented in the LiDAR are large, downed logs. In the lower section of the scene, there is a tangled blowdown of trees. All downed logs were verified with a field visit in 2023. The density of large logs, as revealed with LiDAR, may be an additional signature of old-growth forest.

researchers to explore uses of LiDAR for all kinds of ecological topics. Using LiDAR to answer ecological and conservation questions is a pioneering area of research.

Tracking stands entering the LS class

Because LiDAR for the study area was flown for only one “point” in time (mostly 2015-2018), we have no way of tracking hectares that grow into the Transitioning LS and LS classes. However, the Wheatland Geospatial Lab at the University of Maine has developed a method of generating a 1 m^2 resolution canopy height model from NAIP imagery (National Agriculture Imagery Program).[122] NAIP imagery is publicly available and flown every two or three years. This means that, going forward, we might be able to use NAIP imagery to identify hectares that were not in an LSOG condition on the previous NAIP flight, but now are. This would be particularly interesting to know for public lands (e,g., BPL, Baxter Park) and for private conservation lands (e.g., TNC and AMC). NAIP data provide only a canopy surface model, not the 3-D data of LiDAR. But it appears from our work that the canopy surface model is sufficient for accurately locating LSOG stands. We will still explore the potential to locate true old-growth with the 3-D LiDAR data.

Screening the Organized Townships

We focused this project on the unorganized townships of Maine, in part because that is the area we, as researchers, have the most experience. However, LiDAR could be used in the same way to screen the organized towns of Maine for LSOG. Preliminary reconnaissance in the mid-coast Camden area suggests the approach will work for the organized towns. In organized towns, sometimes former agricultural lands can have very tall second-growth white pine that might “fool” our computer model. But those second growth stands also have a unique LiDAR

We envision an opportunity to combine LSOG conservation with increased investment in silviculture, making the forest even more economically productive.

signature that the computer can likely discern. It is simply a matter of training the computer on known sites (for either inclusion or exclusion). We hope land trusts will consider using LiDAR if they are interested in conserving LSOG forest. We would be happy to assist them.

The importance of a healthy forest products economy to conservation

The authors of this report are supporters of a thriving forest products economy. We do not advocate for conservation of LSOG forest at the expense of the forest products economy, and especially rural community jobs. Indeed, we believe that the many ecological attributes we enjoy today are the result of the long history of Maine's working forest. The good news for national-scale bird conservation that we recently reported is a good example of why keeping Maine's forest products economy healthy is important for our *environmental* values.[32] In the last few decades, Maine's forest products economy has been increasingly vulnerable to global competition. However, we believe in producing forest products in a part of the world—Maine—where we can attend to both our economic and environmental values responsibly. That is why we hope landowners and conservation organizations alike will work with us, and each other, to maintain a healthy forest economy while conserving remaining LSOG forest. We envision an opportunity to combine LSOG conservation with *increased* investment in silviculture, making the forest even more economically productive.

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